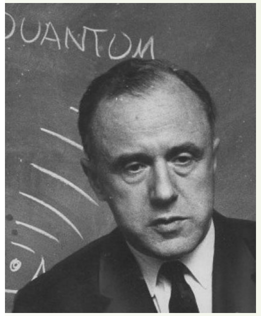
SUPERHEAVY ELEMENTS: PRESENT & FUTURE

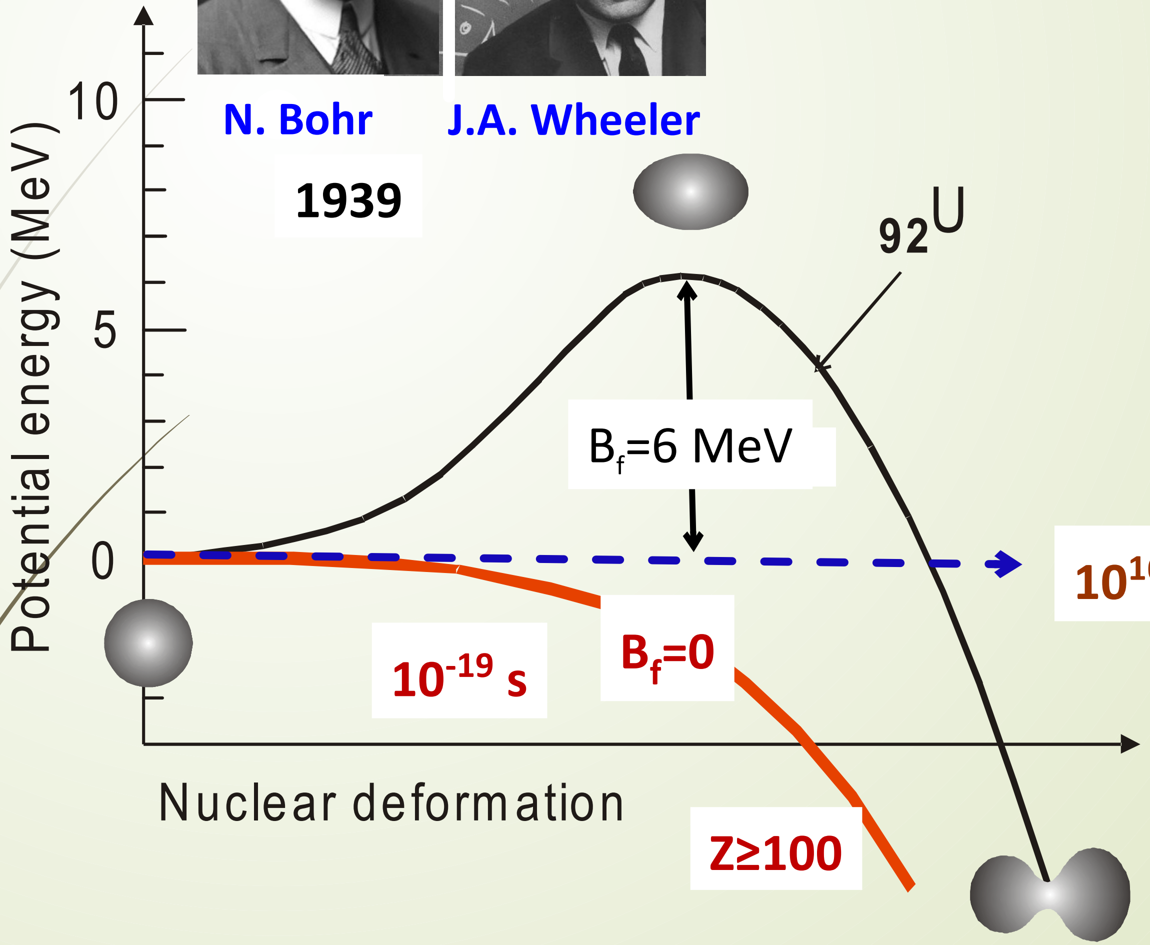
M. ITKIS

Nuclear fission

N. Bohr

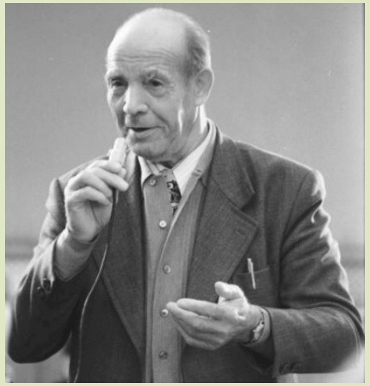


J.A. Wheeler



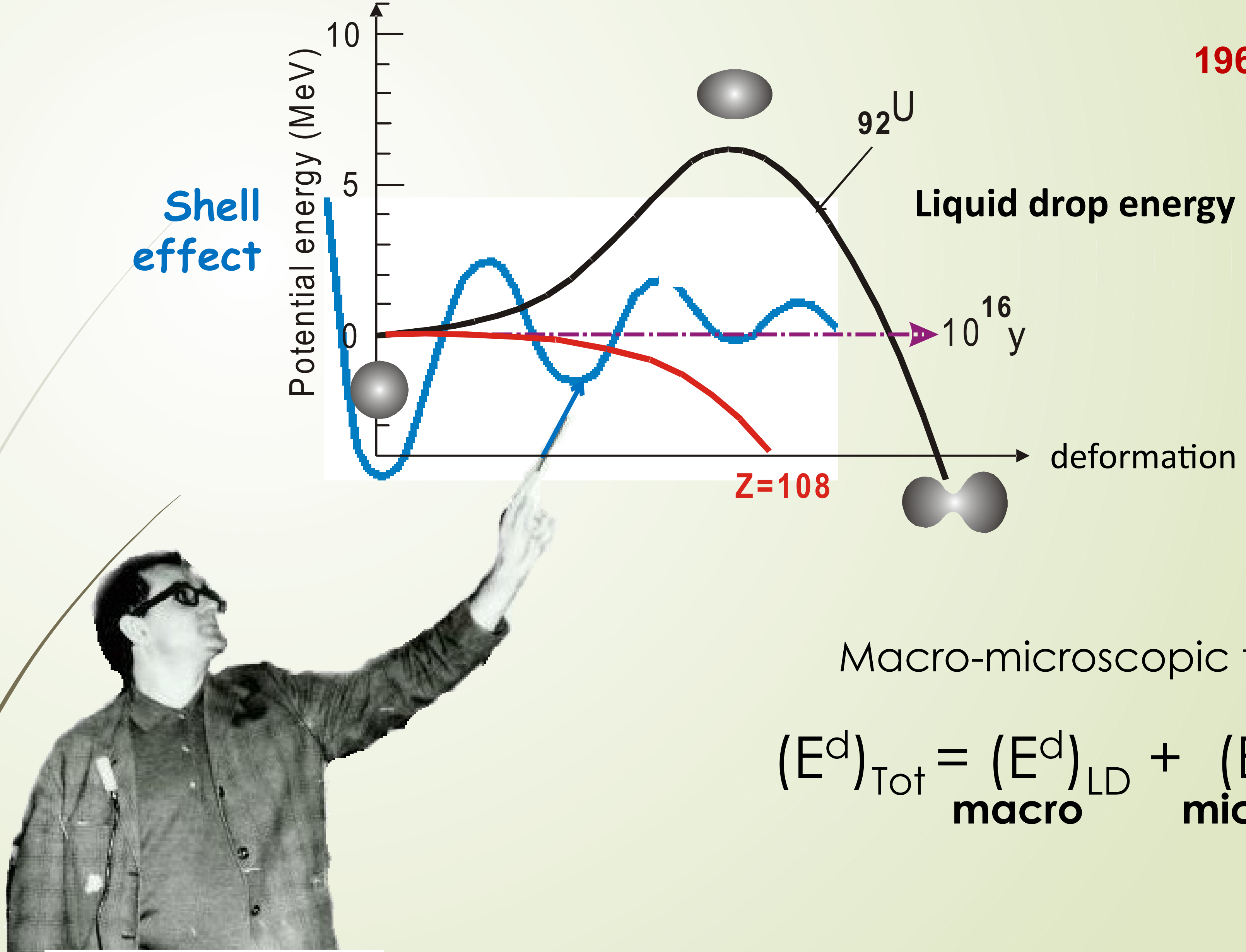
1940

G.N. Flerov



K.A. Petrzhak

1967

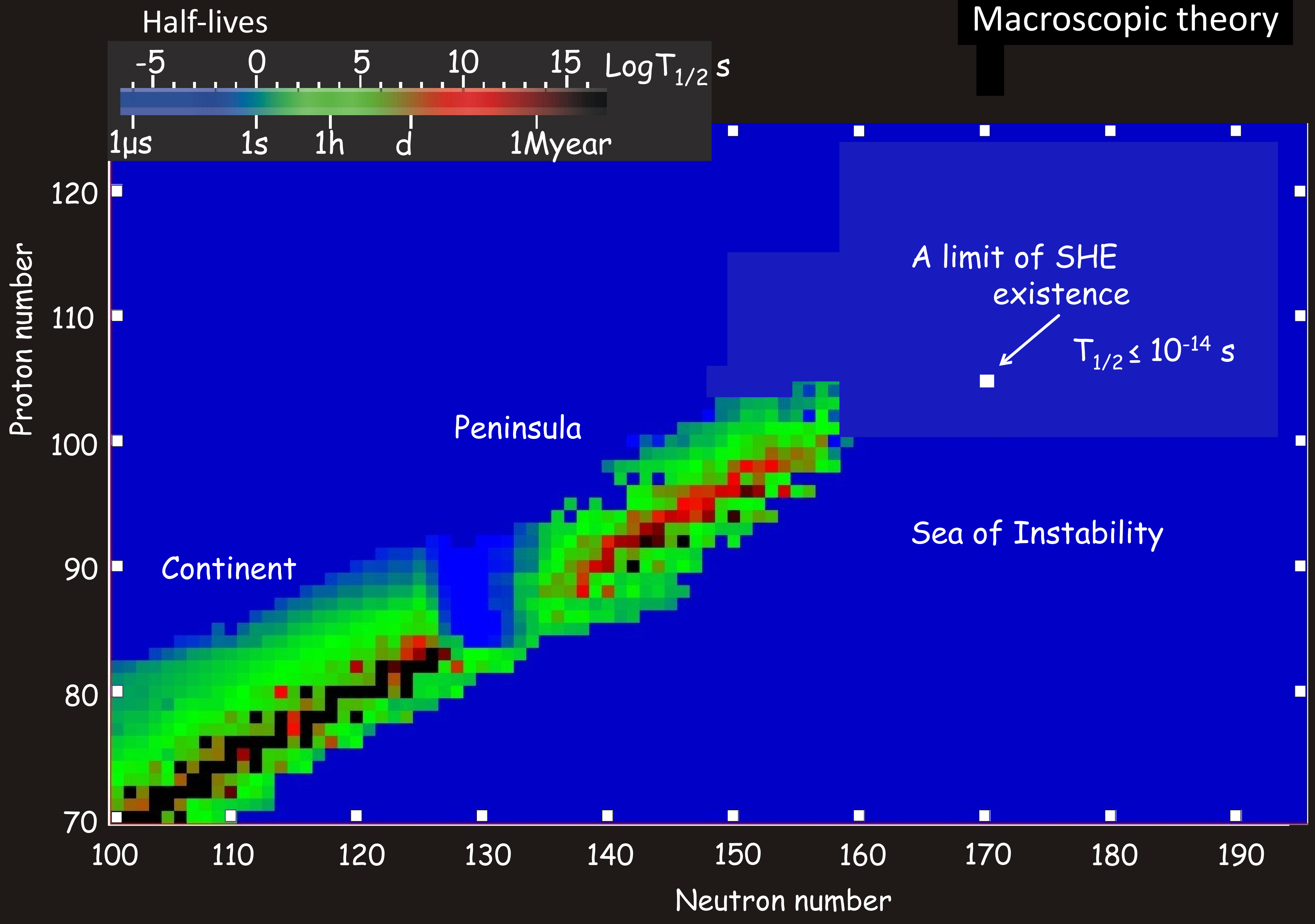


V.M. Strutinski 1967

Macro-microscopic theory

$$(E^d)_{Tot} = \underbrace{(E^d)_{LD}}_{\textbf{macro}} + \underbrace{(E^d)_{Shell}}_{\textbf{micro}}$$

Macroscopic theory



15-year long assault on the "Islands of Stability"

1970-1985

- Los Alamos (USA)
- Berkeley (USA)
- Dubna (JINR)
- Oak Ridge (USA)
- Mainz (Germany)
- Darmstadt (Germany)
- Orsay (France)
- Würenlingen (Switzerland)
- Tokyo (Japan) some later

The task of every laboratory was:

To find the method of producing

Search in nature:

earth/lunar objects, cosmic rays,

Artificial synthesis:

high-flux reactor,
nuclear explosion,
powerful accelerator

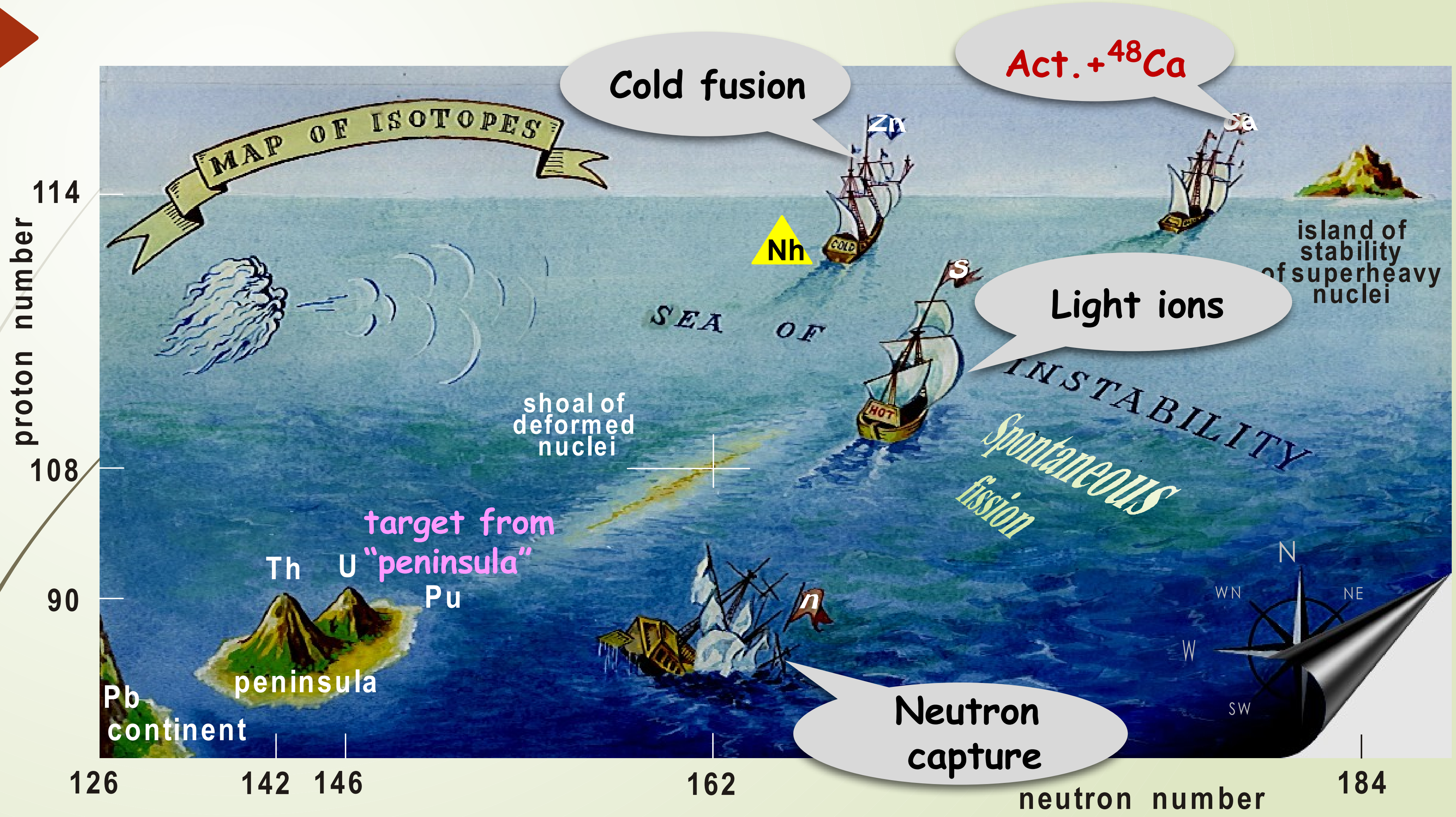
To develop setups:

separator/detector,
spectrometers,
chemical methods, etc.

Unfortunately in all attempts super heavy elements were not found

The problem of artificial synthesis of SHE is related with reaction of synthesis

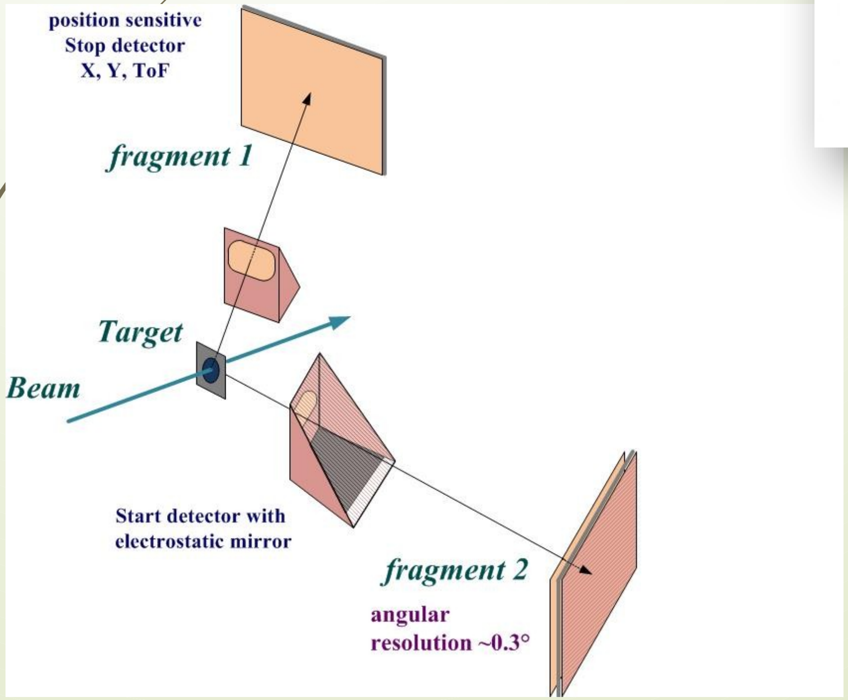
Reactions of synthesis

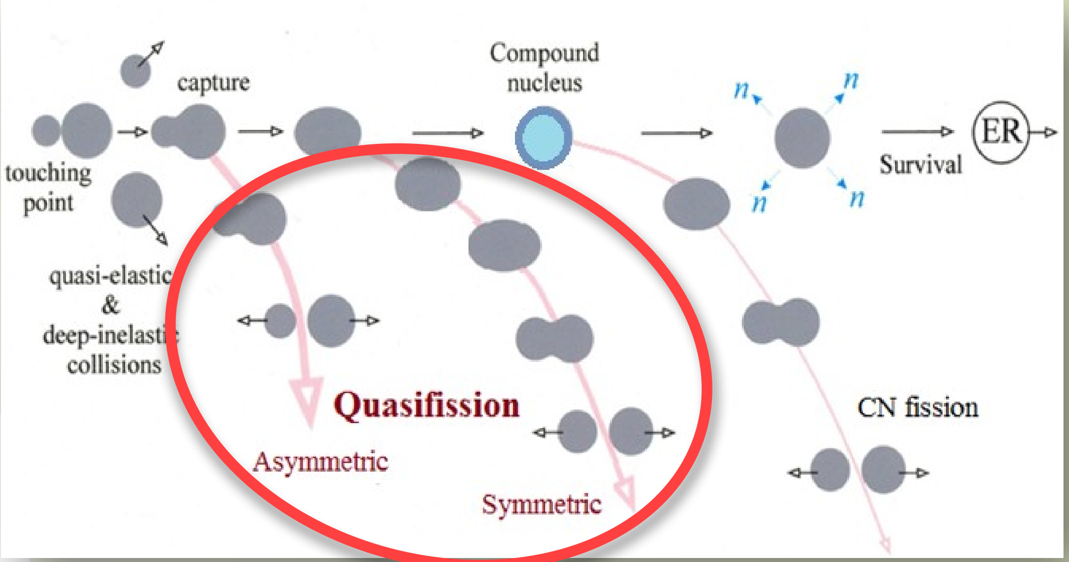


Reaction channels in the collisions of heavy ions

Double arm Time-of-Flight spectrometer CORSET

The study of binary channel of heavy-ion-induced reactions (fusion-fission, quasifission and deep-inelastic processes).

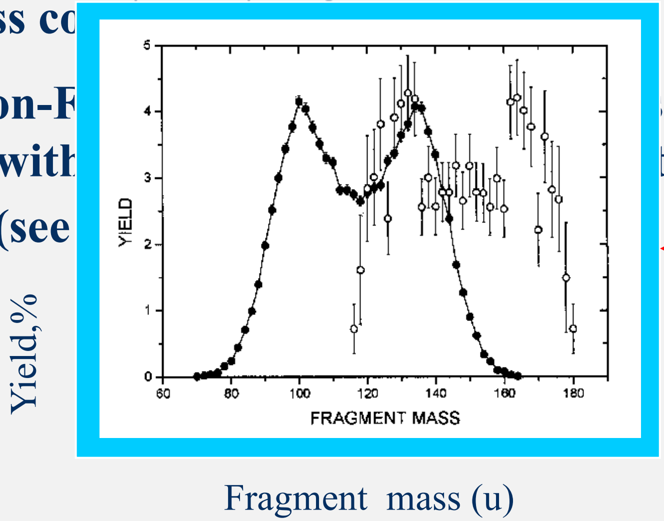


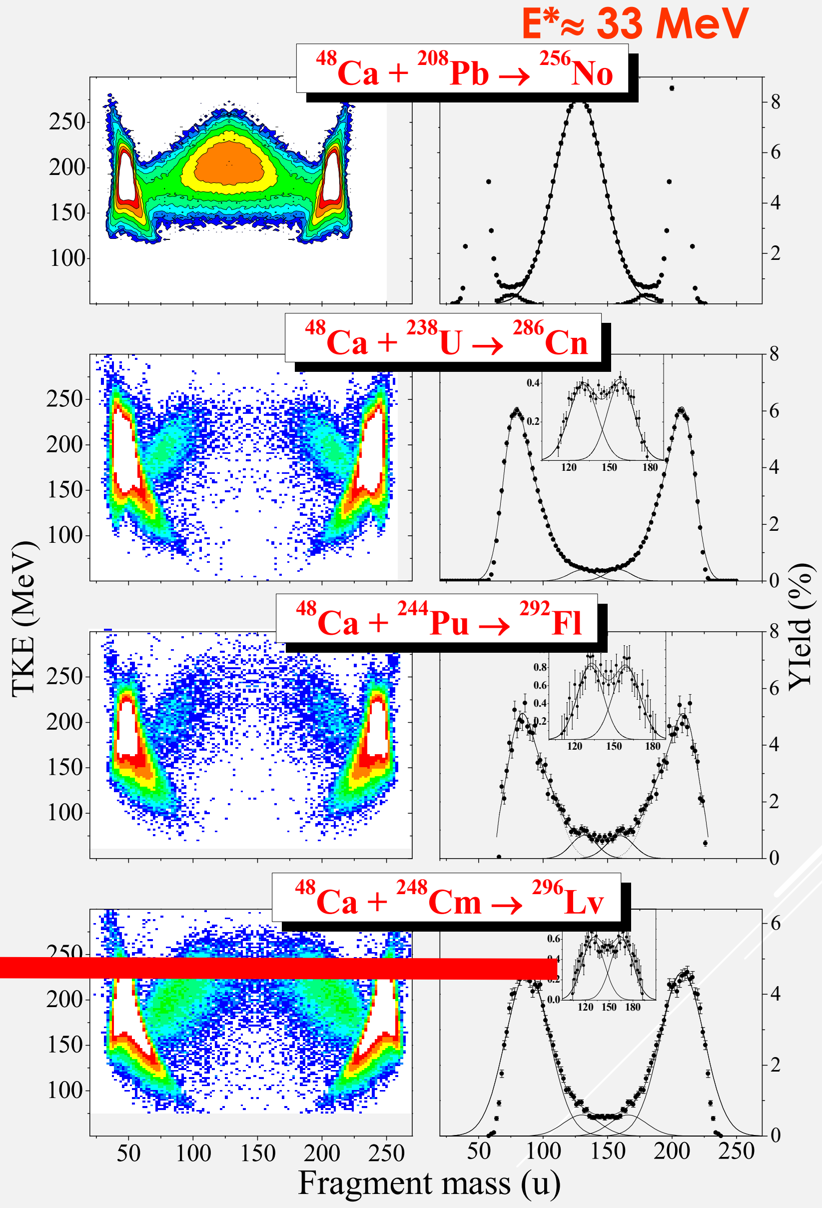


Time resolution	150-180 ps
ToF base	10-30 cm
ToF arm rotation range	15°-165°
Solid angle	100 -200 msr
Angular resolution	0.3°
Mass resolution	**2-4 u**

REACTIONS WITH ^{48}Ca

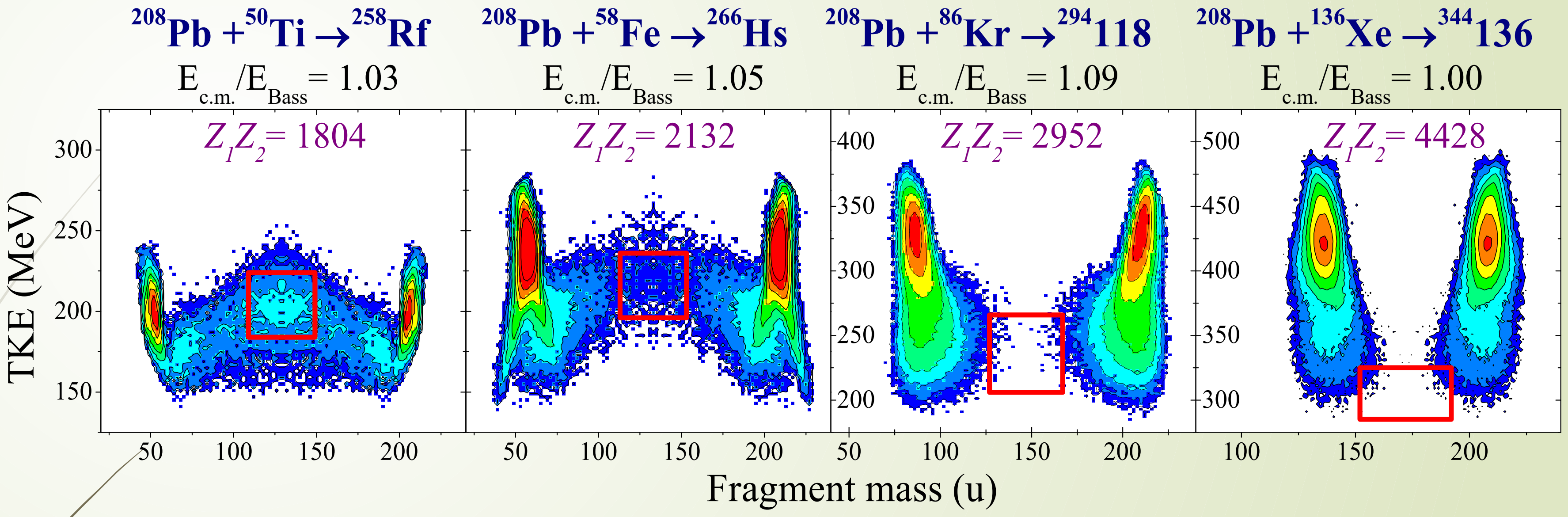
- The sharp change of the MED triangular shape for the reaction ^{48}Ca + ^{208}Pb, where Fusion-Fission process dominates, to the Quasifission shape of MED for the ^{286}112-^{296}116 nuclei.
- The wide two-humped mass distribution with high peak of heavy fragment near double magic lead (M_H≈208) for the Quasifission process.
- In spite of the dominating role of the Quasifission process for these reactions we assume that in the symmetric region of the fragment masses (A/2±20) FF process co
- The Fusion-F ymmetric in shape with t M_L≈132-134 amu (see



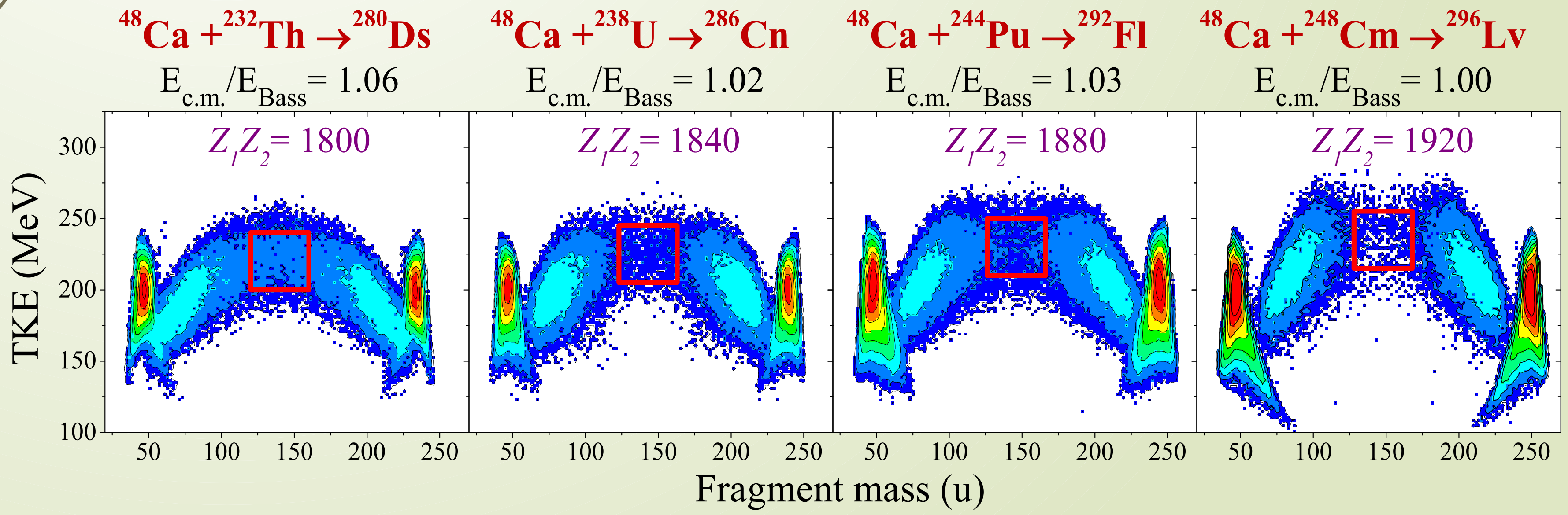


FLNR 1999

Cold fusion reactions



Hot fusion reactions

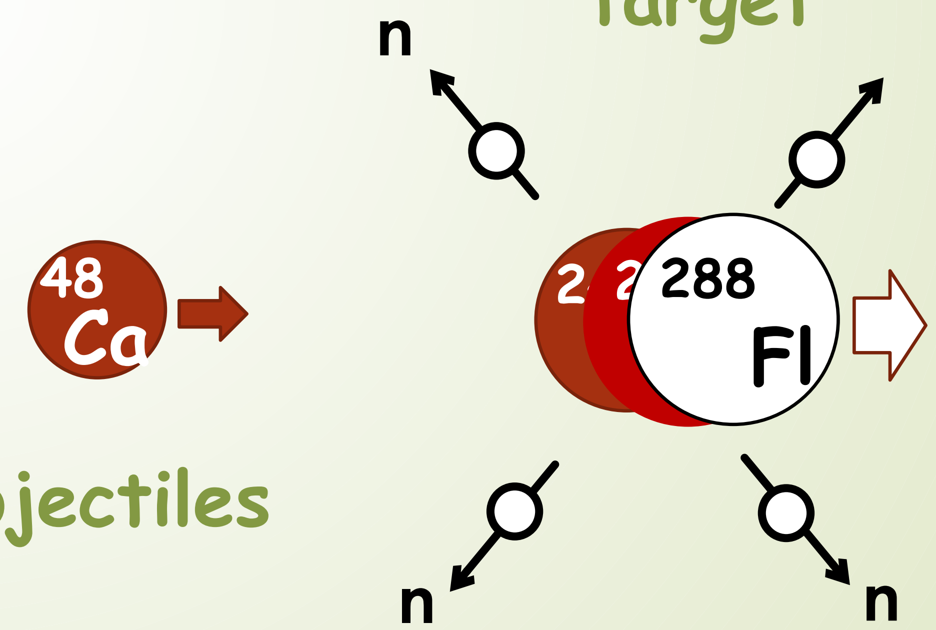


Reaction of synthesis

artificial element made in
high flux nuclear reactor

target

from
accelerator



to separator

projectiles

rare and very
expensive isotope of Ca

fusion & cooling

BEAM

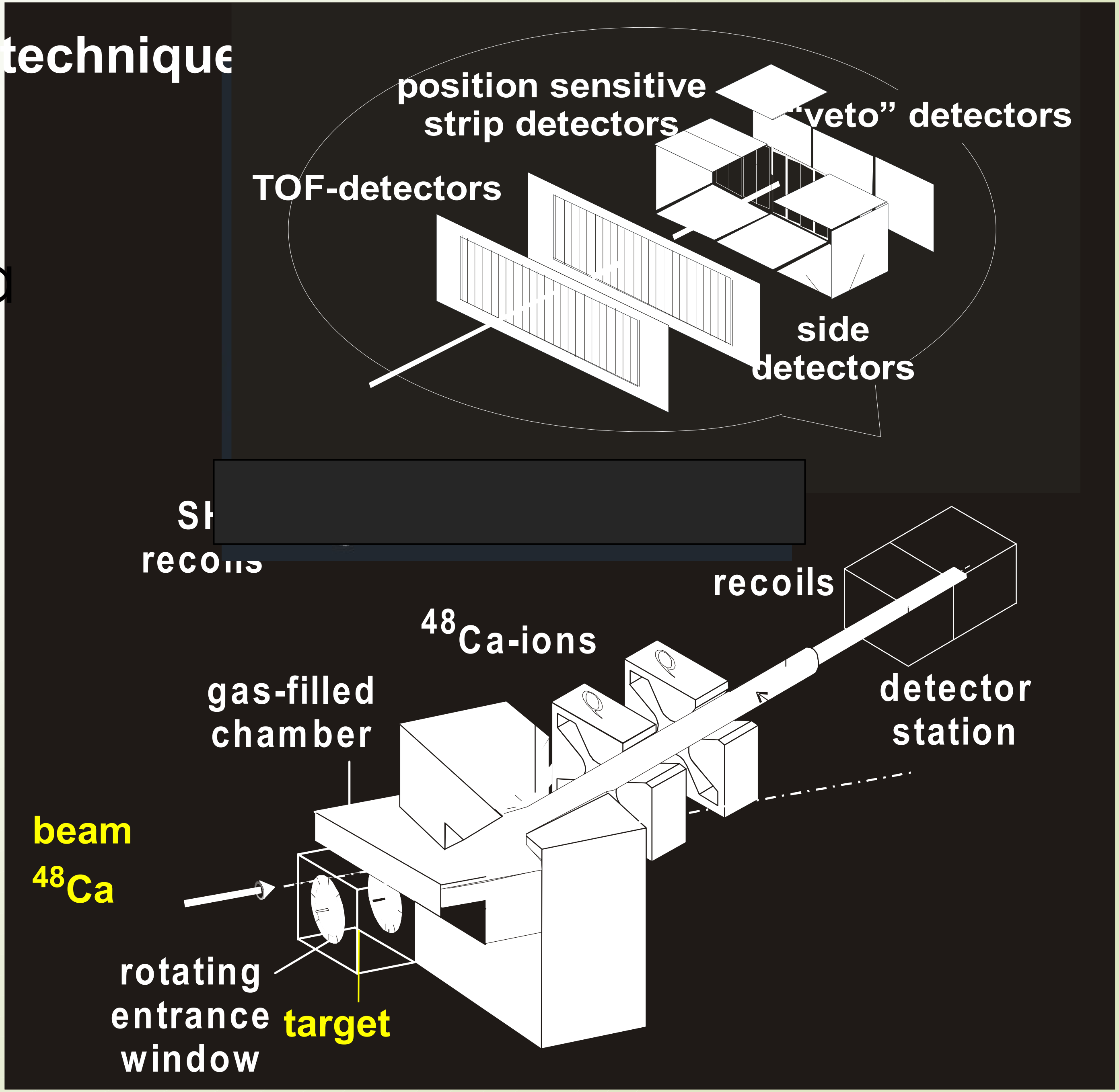
100,000 hours beam time of Ca-48

Heavy Ion Accelerator U-400

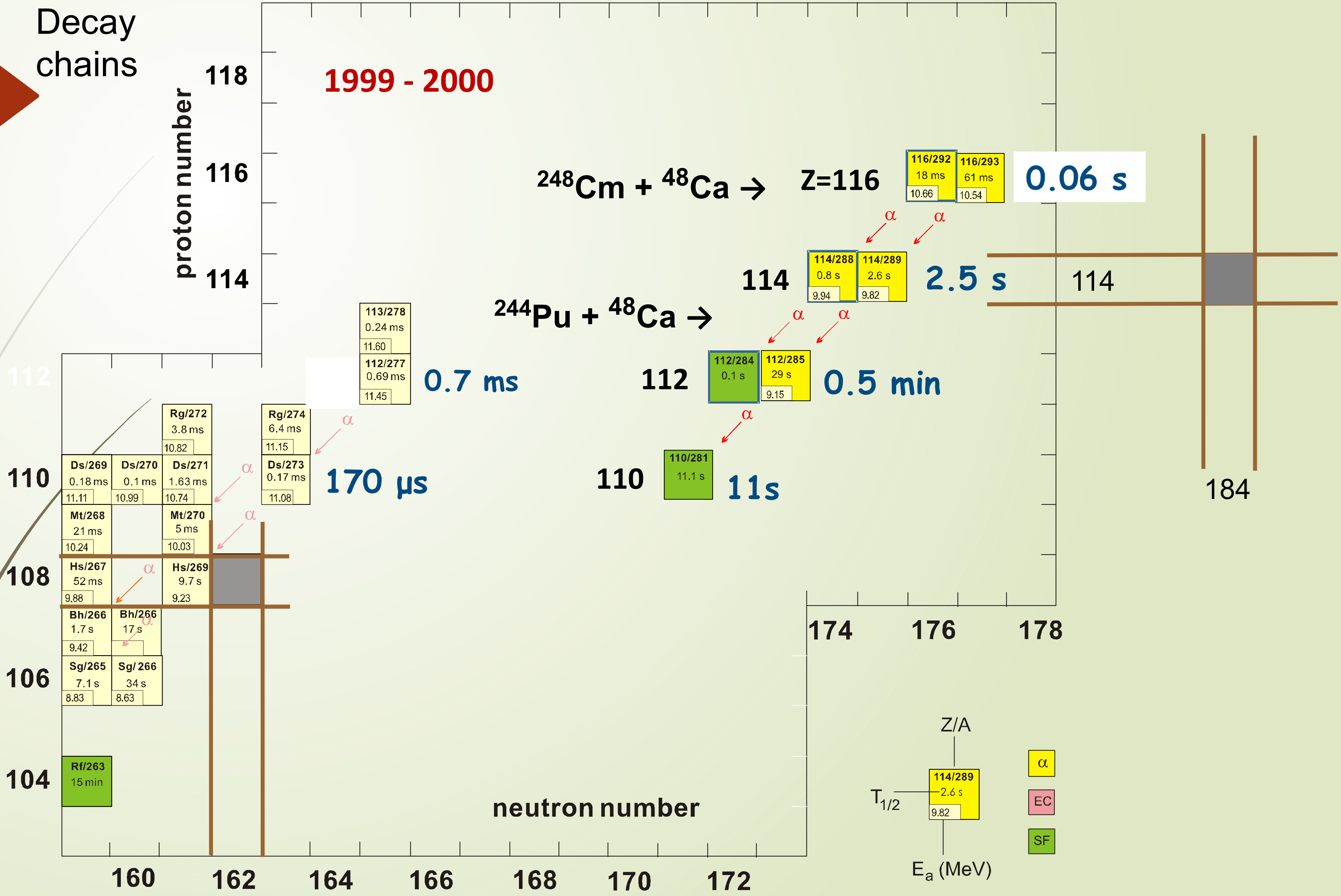
Joint Institute for Nuclear Research (Dubna, Russia)

Experimental I technique

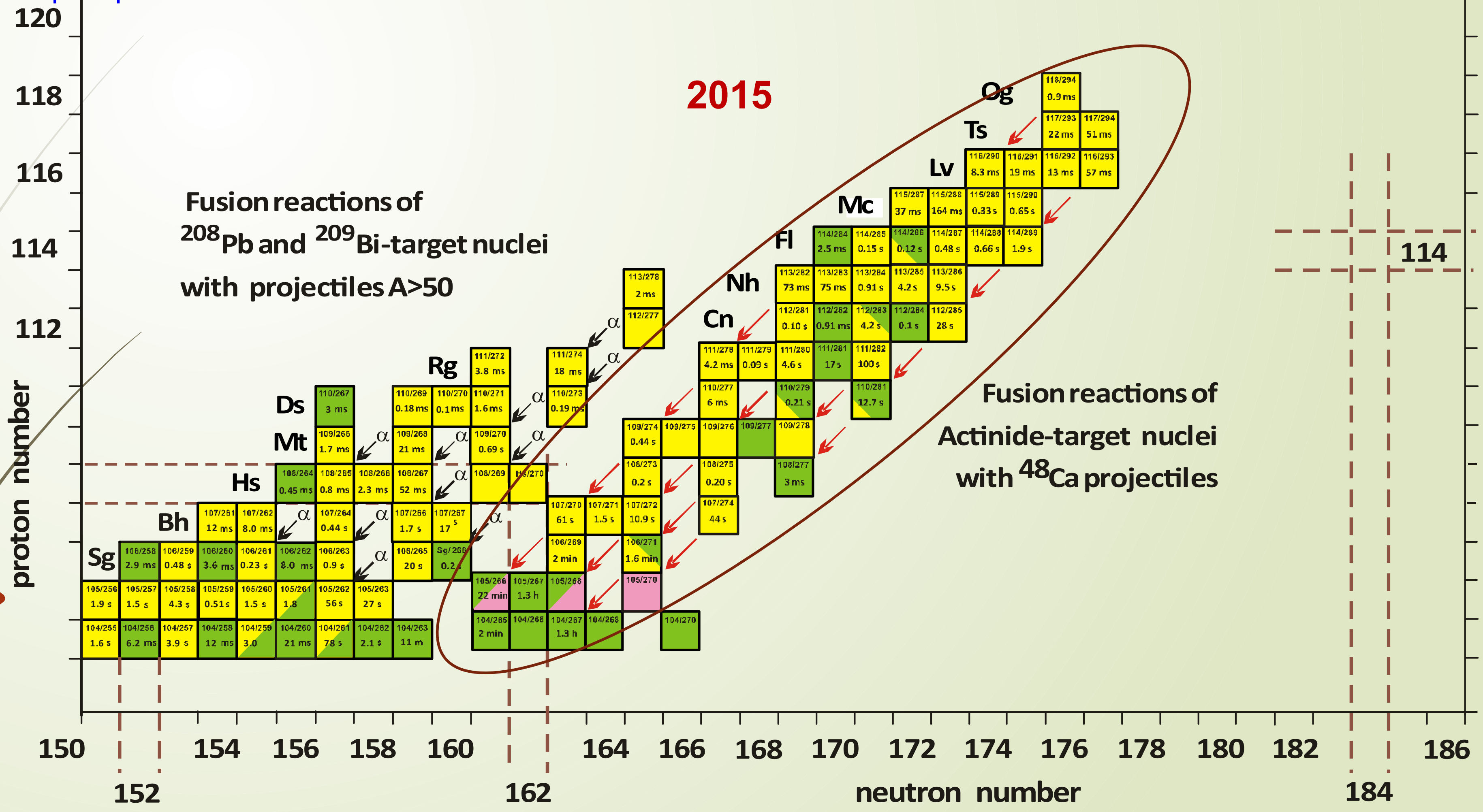
Dubna
Gas
Filled
Recoil
Separator



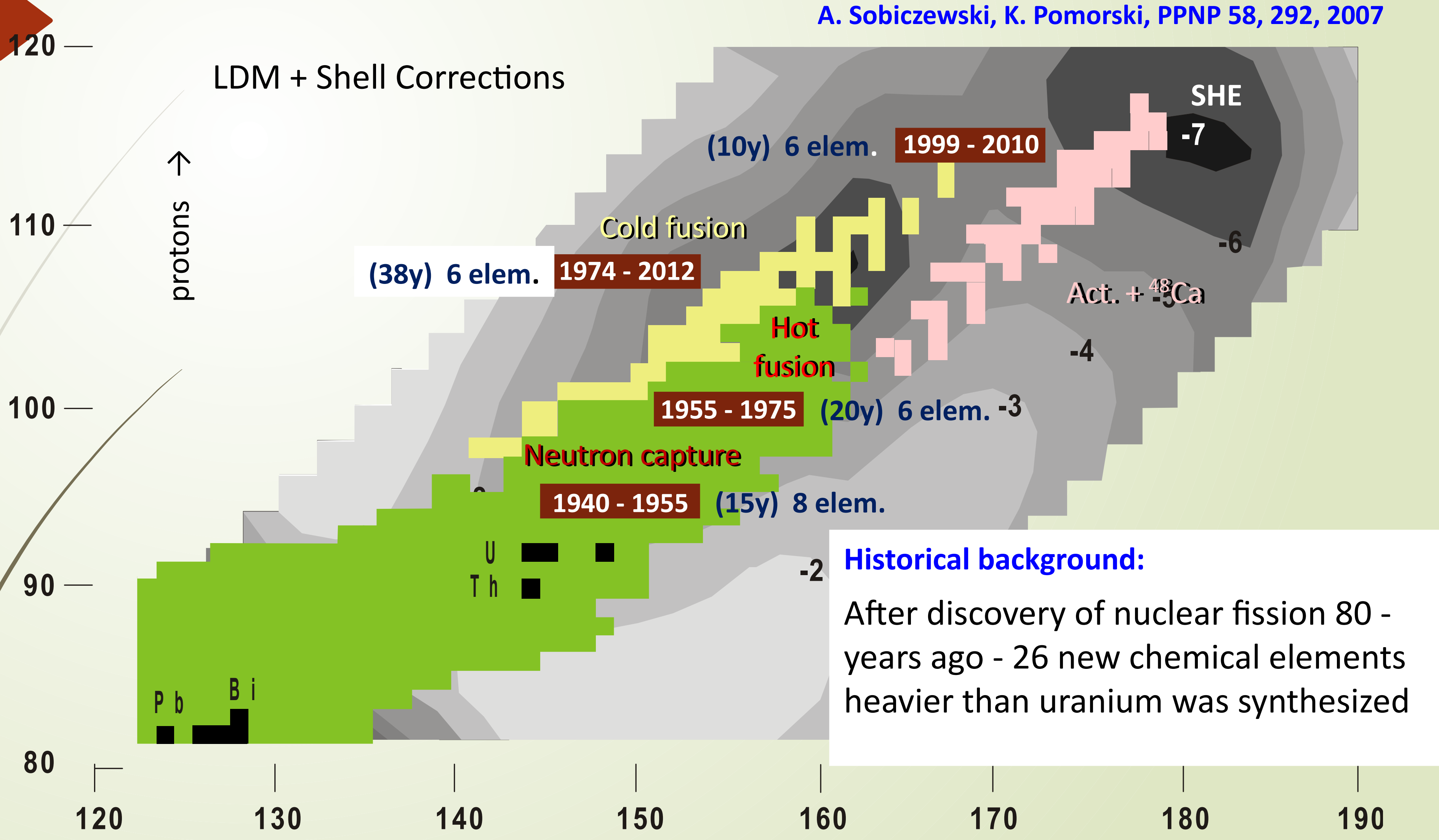
Decay chains



Super heavy islanders and their daughter products are a large family of the 55 new neutron-rich isotopes with unique properties.



Reactions of Synthesis



Historical background:

After discovery of nuclear fission 80 - years ago - 26 new chemical elements heavier than uranium was synthesized

With Z > 40% larger than that of Bi, the heaviest stable element, we see an impressive extension in nuclear survivability.

Although SHN are at the limits of Coulomb stability,

- shell stabilization lowers ground-state energy,
- creates a fission barrier,
- and thereby enables SHN to exist.

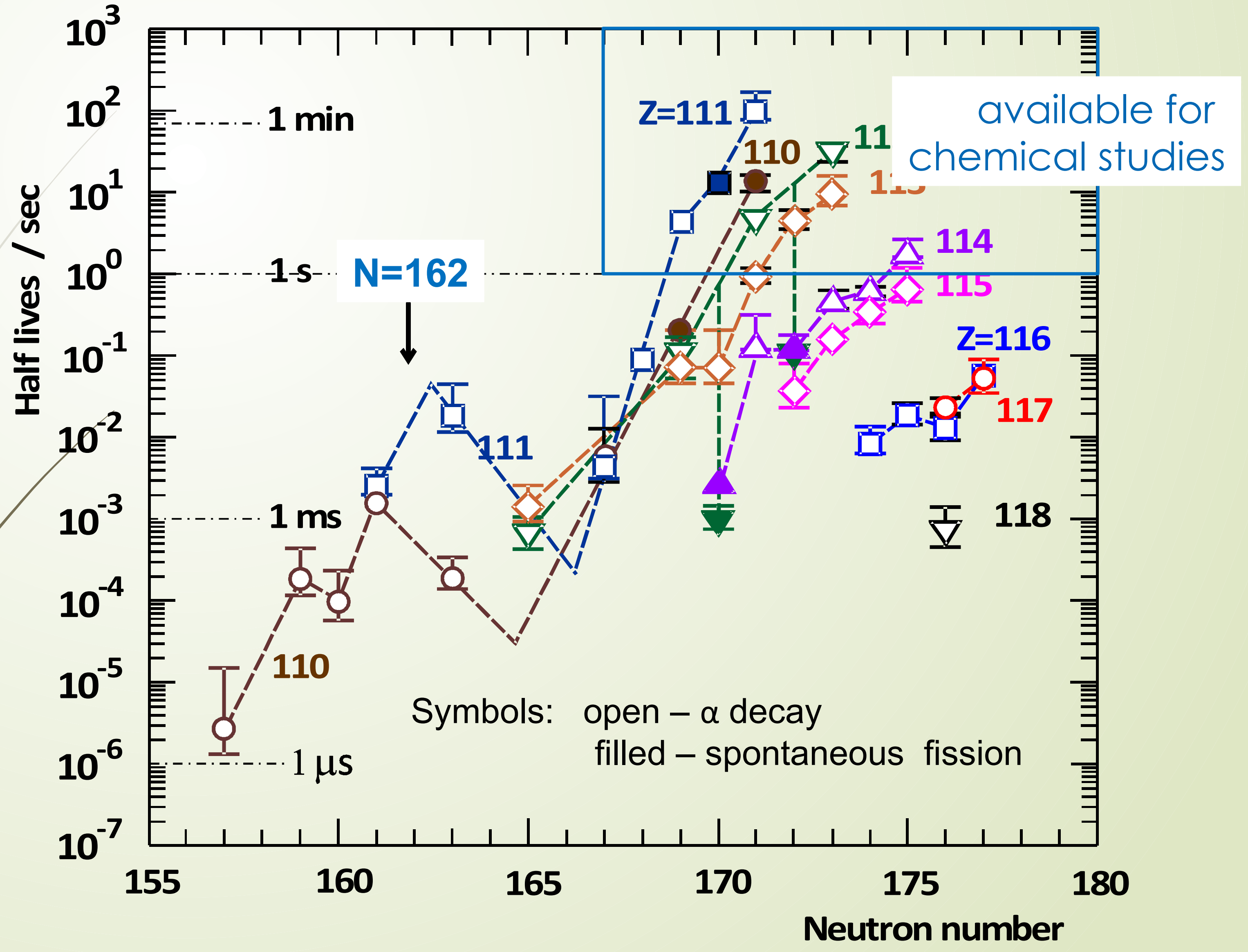
The fundamentals of the modern theory concerning the mass limits of nuclear matter have obtained experimental verification

Where are the super heavy elements located in the Periodic Table?

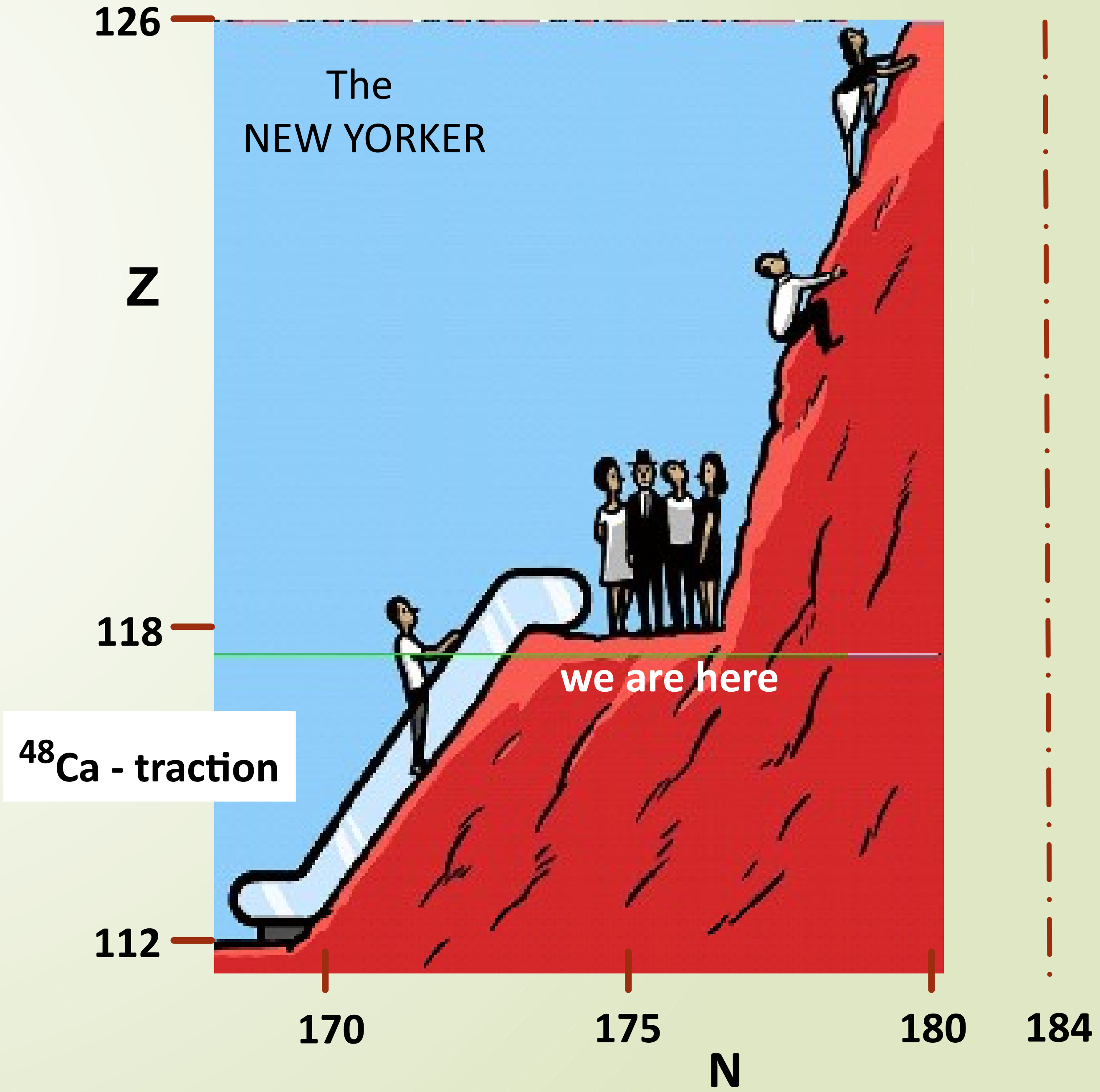
Are they similar to their light homologues?

Where is the boundary of the Periodic Table and how many elements can it contain?

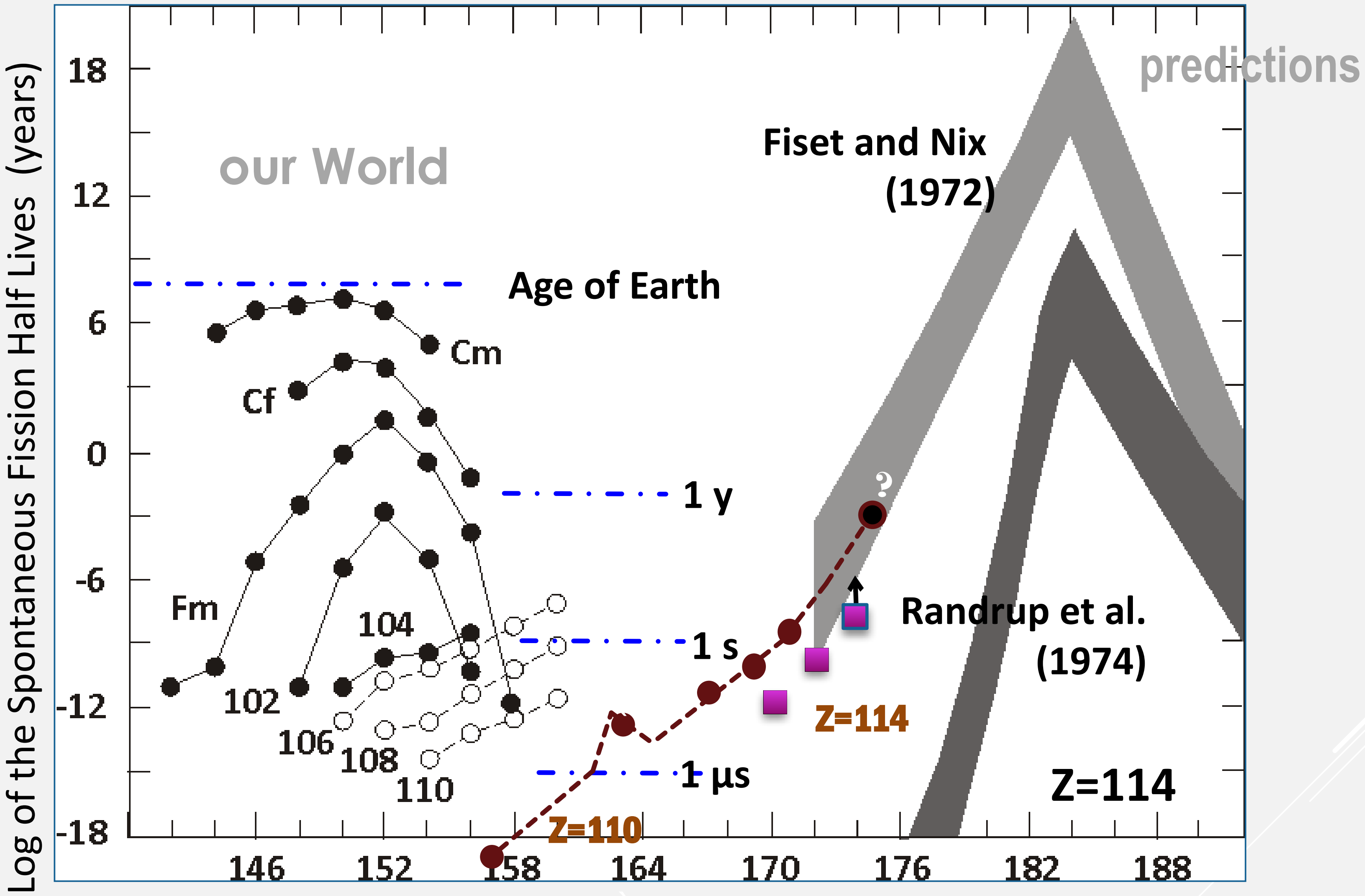
Decay modes and the half-lives of the isotopes with Z ≥ 110



PRESENT

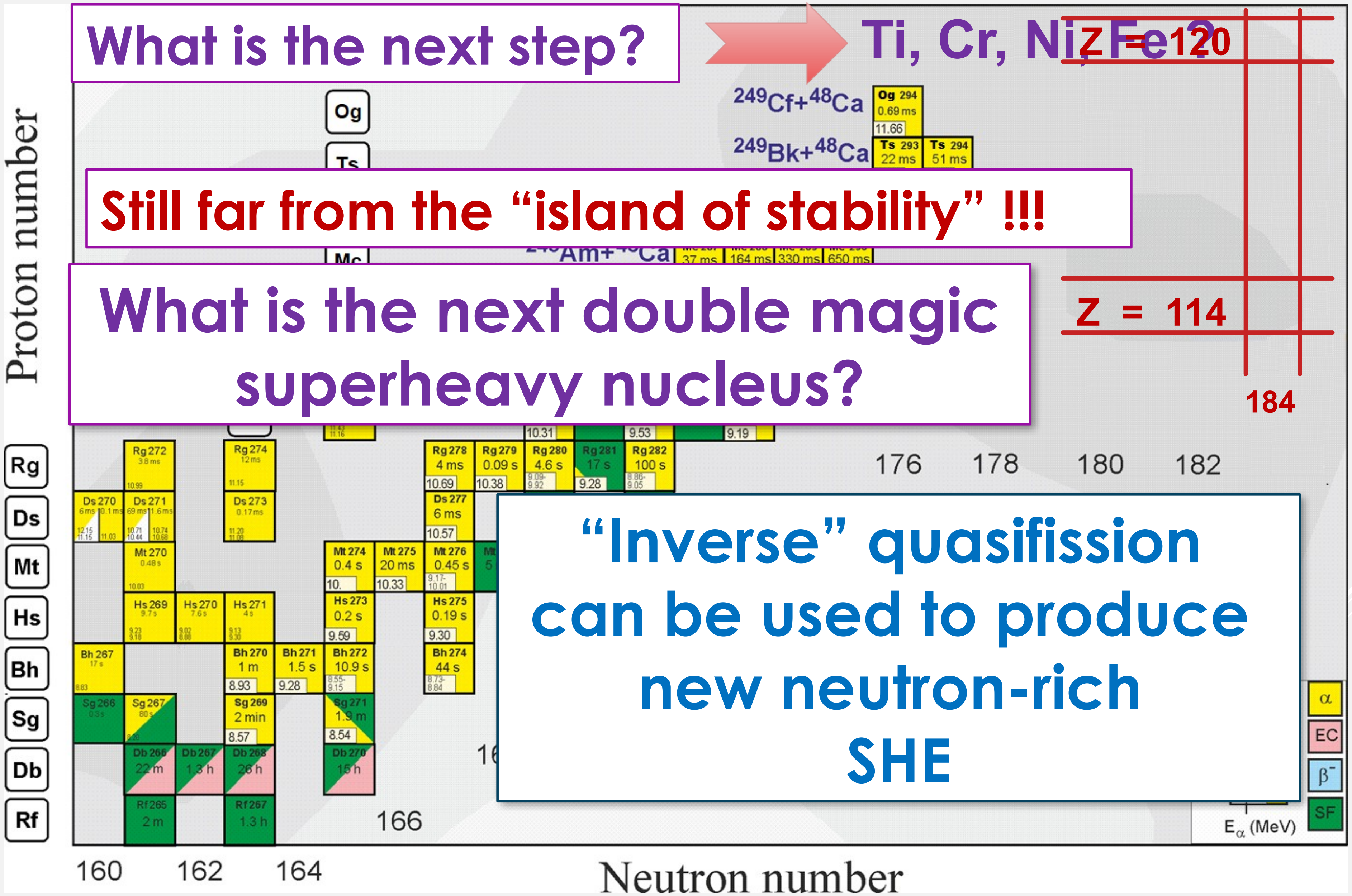


126
Z
118
112
The
NEW YORKER
we are here
48Ca - traction
170
175
180
184
N



Neutron number

* Search for superheavies



What is the next step?

Still far from the "island of stability" !!!

What is the next double magic superheavy nucleus?

"Inverse" quasifission can be used to produce new neutron-rich SHE

FLNR ACCELERATOR COMPLEX


1
March 2012, Dubna

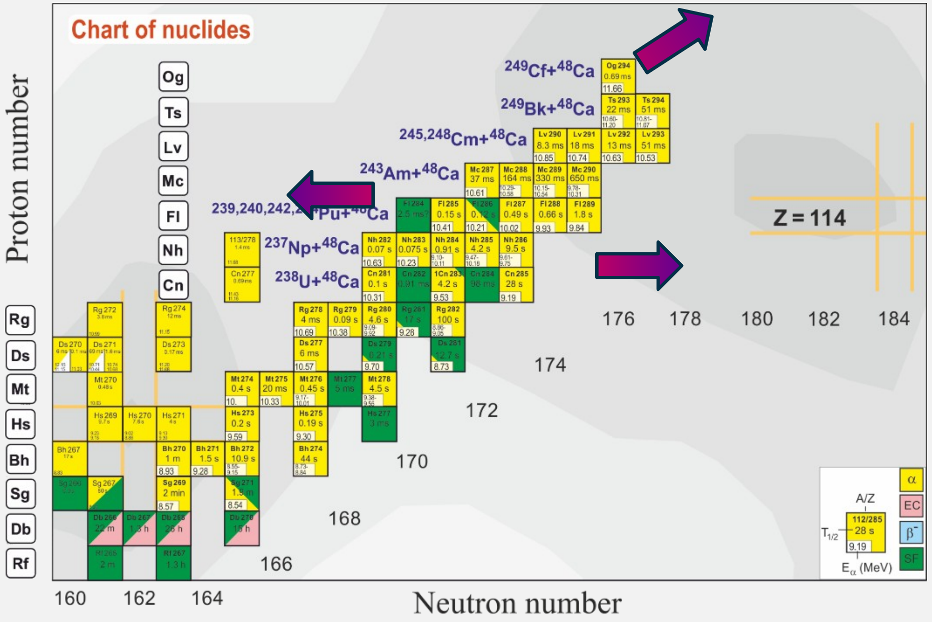
SHE research: Main tasks

Experiments at the extremely low (σ<100 fb) cross sections:

- Synthesis of new SHE with Z = 119 and 120 in reactions with ^{50}Ti, ^{54}Cr ...;
- Synthesis of new isotopes of SHE;
- Study of decay properties of SHE;
- Exploring limits the Island of Stability;
- Study of excitation functions.

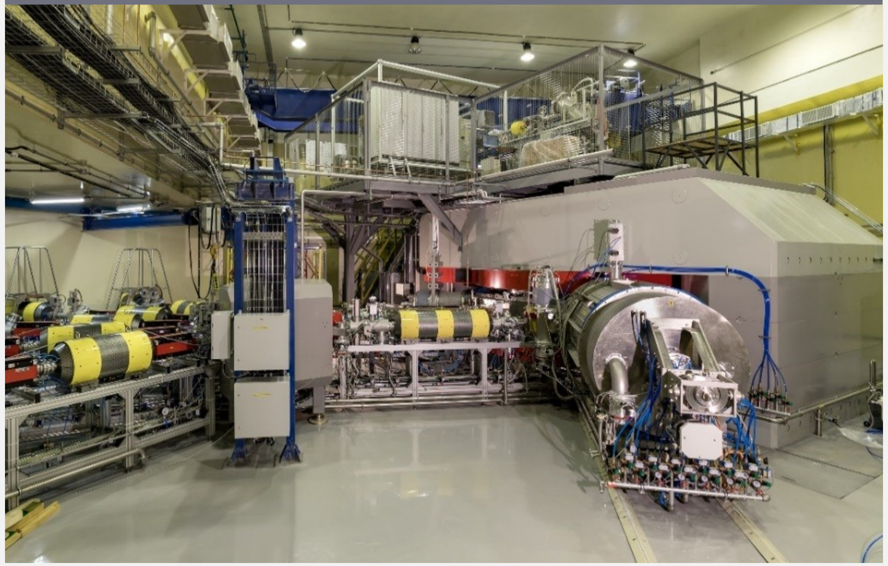
Experiments requiring high statistics:

- Nuclear spectroscopy of SHE;
- Precise mass measurements;
- Study of chemical properties of SHE.

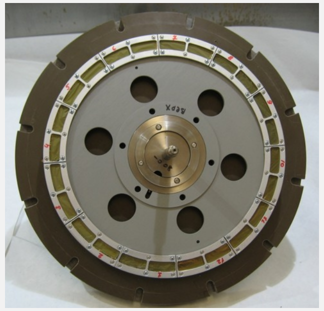


Beam of ^{48}Ca @ DC-280:

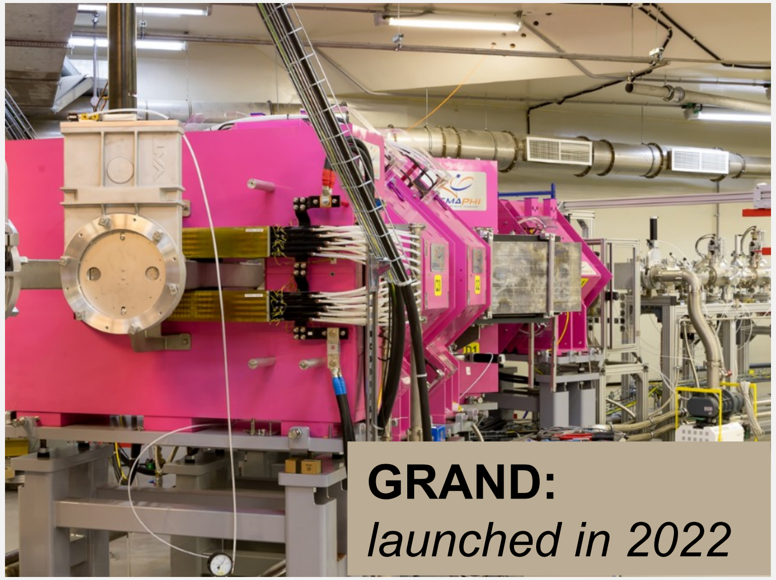
- *Intensity: up to 6·10^{13} ions/s, 10 pμA*
- *Energy: 5 - 8 A·MeV*
- *Efficiency: ~50%*

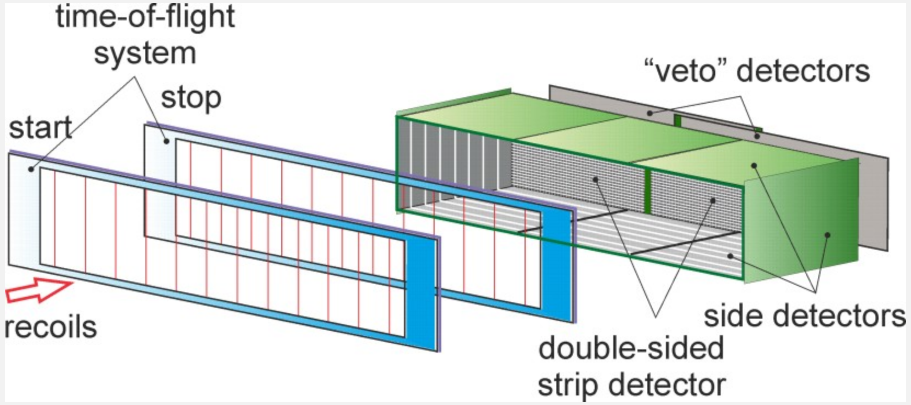


Separators @ SHE Factory

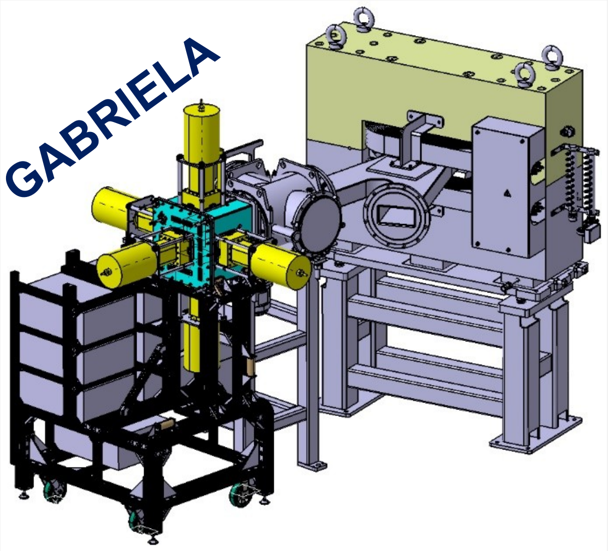


24-cm target wheel
12 sectors





48×220 DSSD & 60×120 SSSD



5 Ge Clover detectors

116 ^{3}He counters

Transmission:

From $^{206}Pb(^{48}Ca,2n)^{252}No$ test reaction:
55±7%
Cross section

From $^{243}Am(^{48}Ca,2\text{-}3n)^{288,289}Mc$ reaction:

Comparison of results at the same ^{48}Ca energy

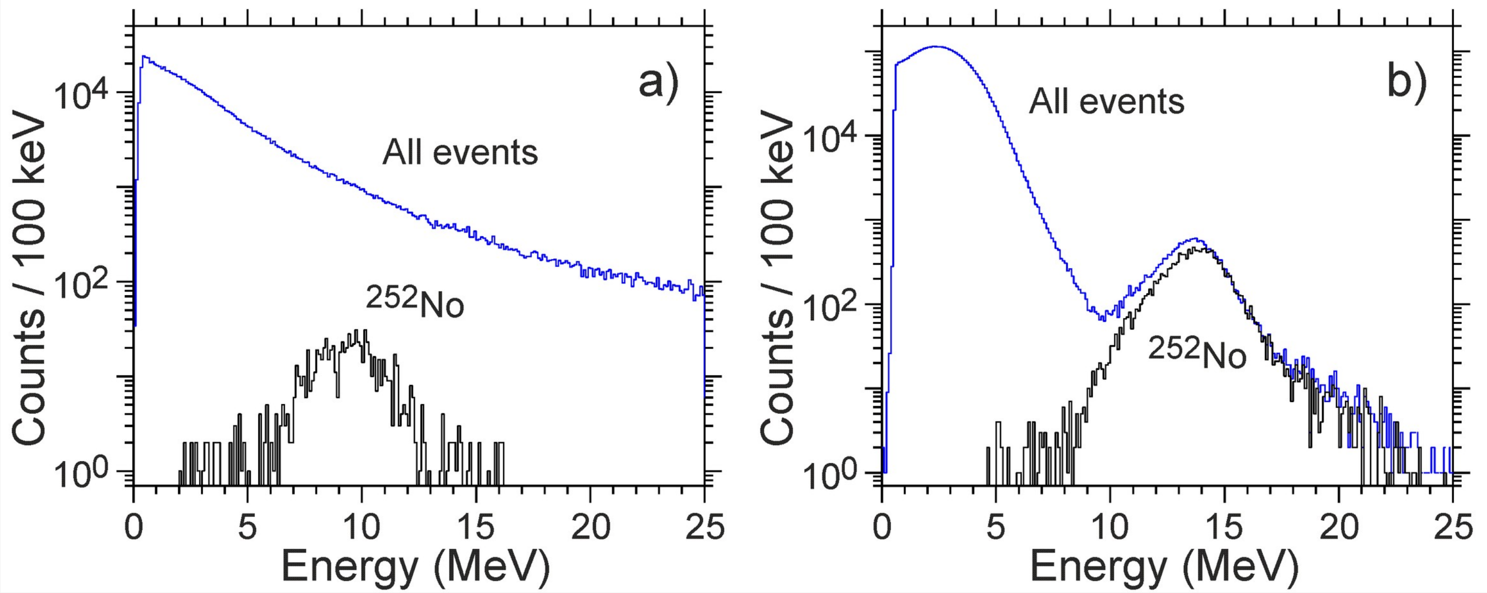
	DGFRS	DGFRS-2
Target thickness, mg/cm^2	0.37	0.43
Beam dose, 10^{18}	3.3	3.4
No decay chains	^{288}Mc – 6 ^{289}Mc – 0	^{288}Mc – 13 ^{289}Mc – 2
Yield	1	1.8-2.1

Test reaction:

$^{206}Pb + ^{48}Ca \rightarrow ^{252}No$

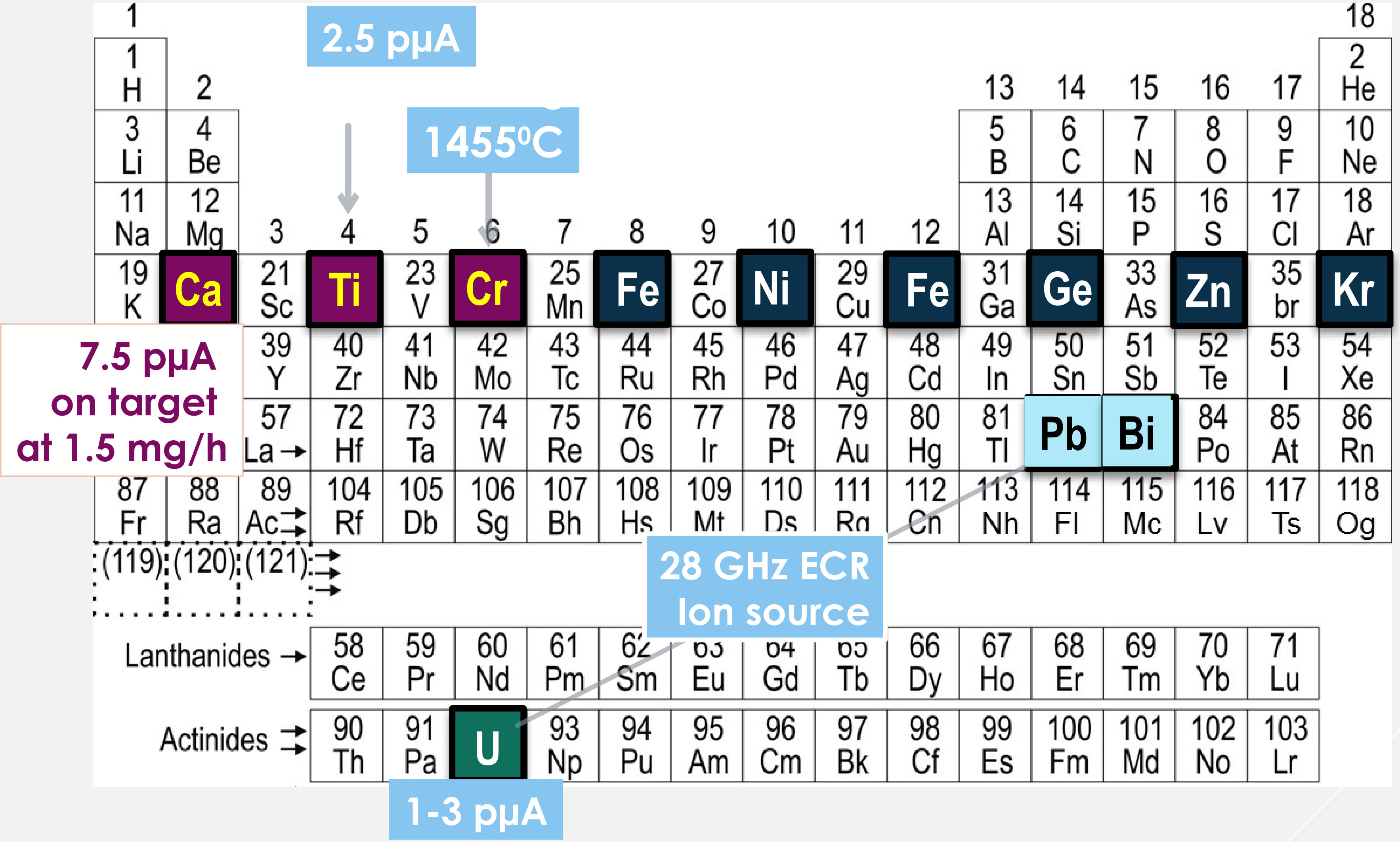
Cross section 0.5 μb

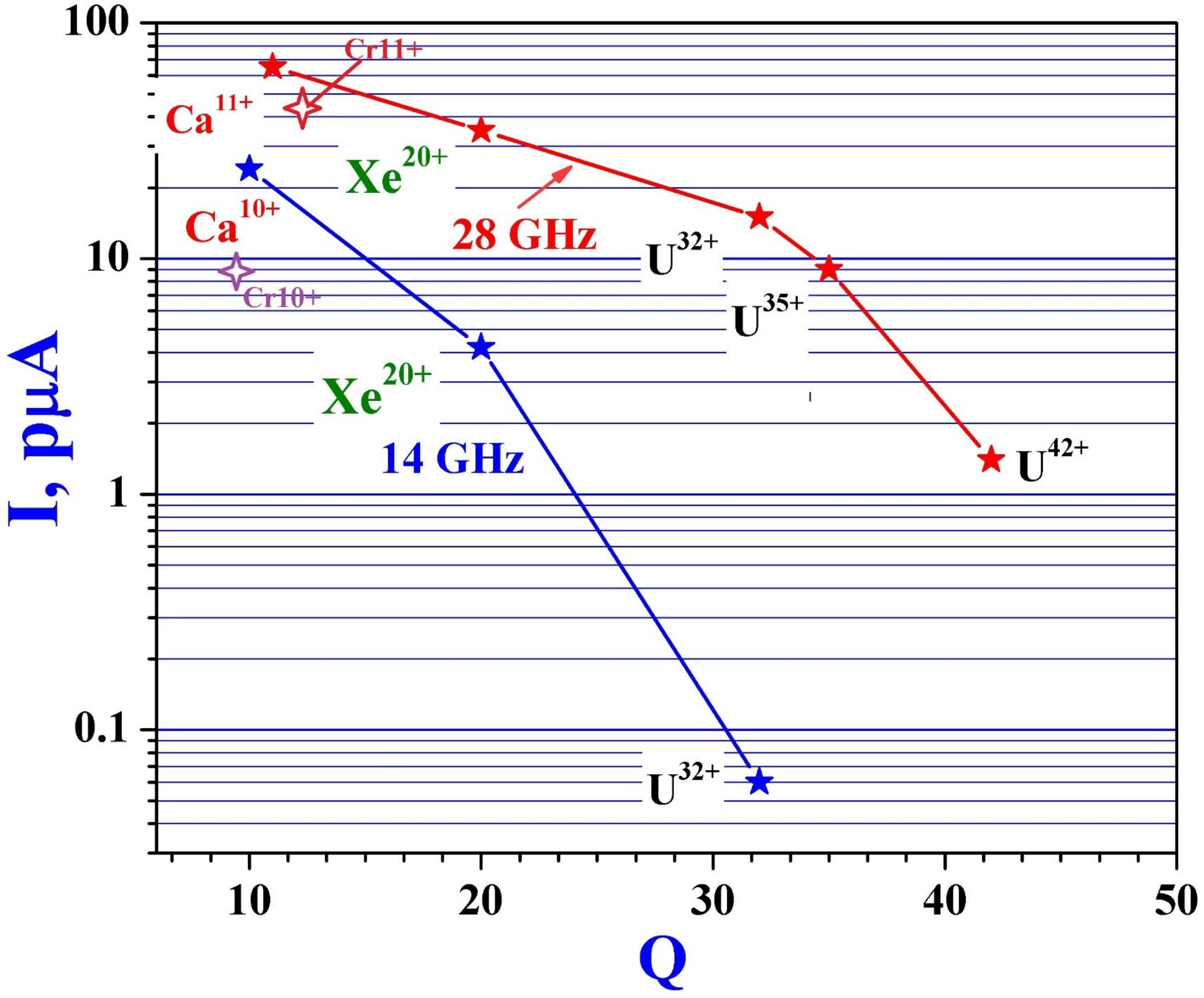
Increase of suppression of background nuclei
by more than factor of 200



Energy spectra of all the particles registered by MWPC (top blue line) and of ^{252}No (bottom black line) nuclei produced in the $^{206}Pb(^{48}Ca,2n)$ reaction using separators DGFRS (a) and DGFRS-2 (b).

Ion Beams


2.5 pμA
1455⁰C
7.5 pμA
on target
at 1.5 mg/h
28 GHz ECR
Ion source
1-3 pμA
Ca
Ti
Cr
Fe
Ni
Fe
Ge
Zn
Kr
Pb
Bi
U
Lanthanides
Actinides


I, pμA
Q
100
10
1
0.1
10
20
30
40
50
Cr11+
Ca11+
Xe20+
Ca10+
28 GHz
Cr10+
U32+
U35+
Xe20+
14 GHz
U42+
U32+

SHE-Factory

joining of efforts

Isotope production:
Cm-248
Bk-249
Cf-251

To be increased
10 times

New accelerator
High beam
dose of : Ca-48
Ti-50
Ni-64

Factor 10

Depend of
target durability

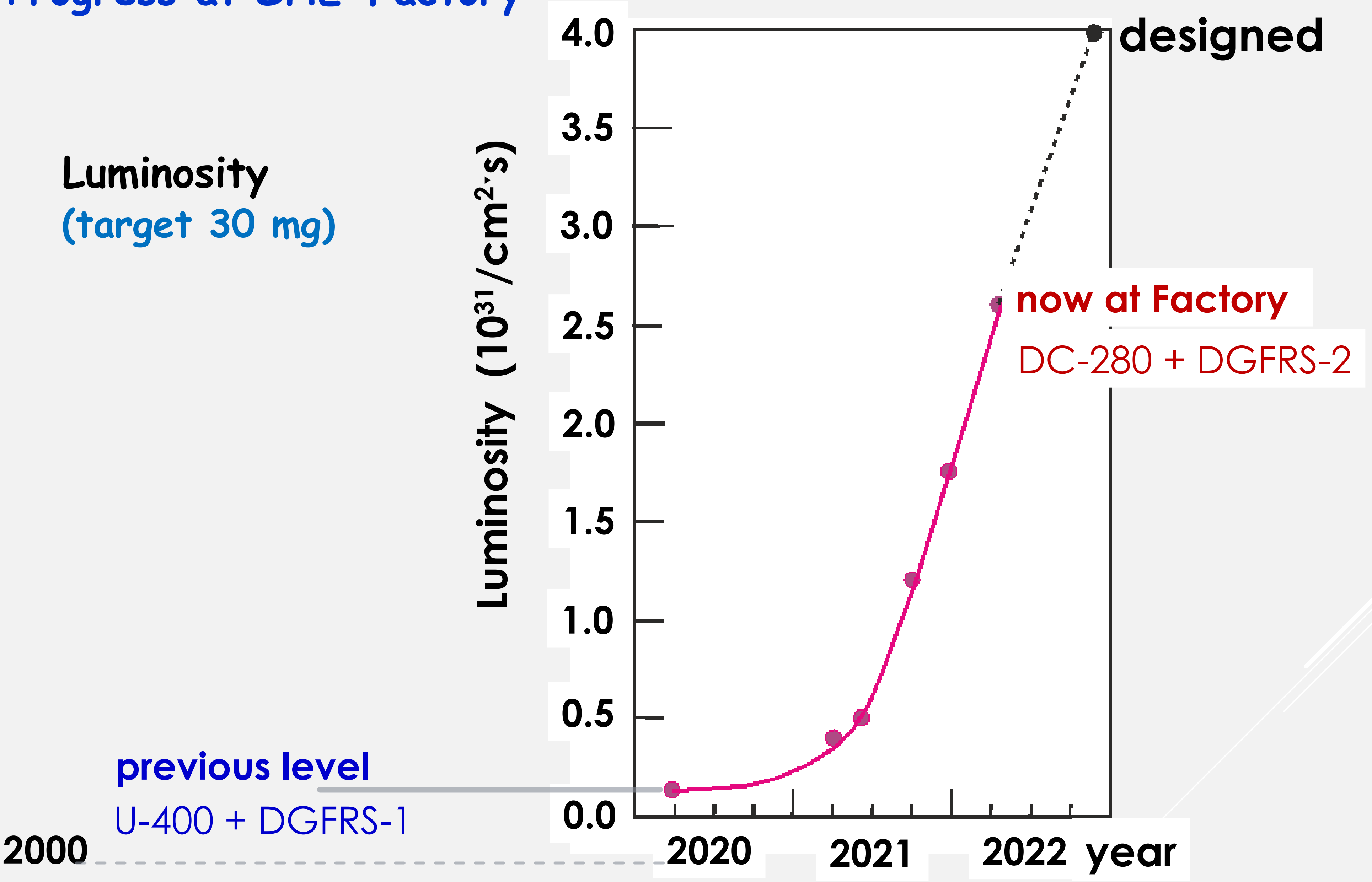
SC- recoil separator
equipped with
Gas Catcher
On-line separator
& sophisticated
Detectors

Factor 3

is closely linked
to the intellect

Progress at SHE-Factory

Luminosity
(target 30 mg)



Summary of experiments @ Superheavy Element Factory in 2020-2023

Experiments:

110: $^{232}Th + {}^{48}Ca \rightarrow {}^{280}Ds^*$, $^{238}U + {}^{40}Ar \rightarrow {}^{278}Ds^*$

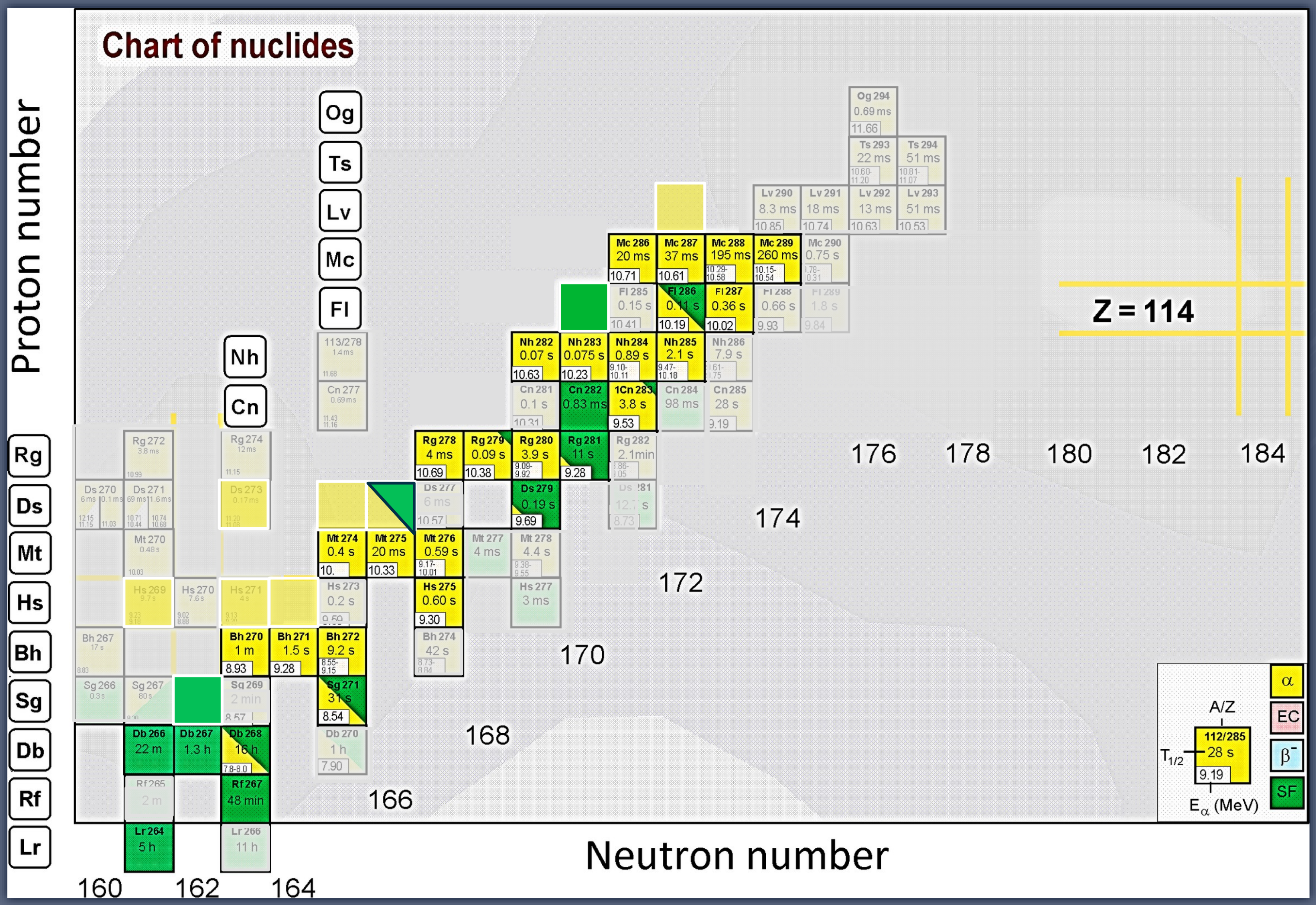
112: $^{238}U + {}^{48}Ca \rightarrow {}^{286}Cn^*$

114: $^{242}Pu + {}^{48}Ca \rightarrow {}^{290}Fl^*$

115: $^{243}Am + {}^{48}Ca \rightarrow {}^{291}Mc^*$

116: $^{238}U + {}^{54}Cr \rightarrow {}^{292}Lv^*$

- ~250 new events of synthesis of superheavy nuclides;
- Decay properties 42 isotopes;
- New isotopes: ^{288}Lv, ^{286}Mc, ^{264}Lr, ^{275}Ds, ^{276}Ds, ^{272}Hs , ^{268}Sg;
- New decay modes: ^{268}Db (alpha-decay), ^{279}Rg (spontaneous fission);
- Indication of the 1st excited state in ^{282}Cn;
- Test of target stability up to 6.5 pμA of ^{48}Ca;



Synthesis of elements 119 and 120
Synthesis of neutron-deficient/rich SH nuclei

Reactions (new elements):

$^{249}Bk(^{50}Ti,xn)\ ^{299-x}119$

$^{249-251}Cf(^{50}Ti,xn)^{(299-301)-x}120$

$\mathbf{^{245,248}Cm(^{54}Cr,xn)^{299,302-x}120}$

Test reactions:

$\mathbf{^{238}U + {}^{54}Cr \rightarrow {}^{292}Lv^*}$

$^{242}Pu + {}^{50}Ti \rightarrow {}^{292}Lv^*$

$^{245}Cm + {}^{48}Ca \rightarrow {}^{293}Lv^*$

$\sigma_{3n} = 4pb$

Reactions (n-deficient):

$^{241}Am(^{48}Ca,xn)^{289-x}Mc$

$^{235}U(^{48}Ca,xn)^{283-x}Cn$

$^{231}Pa(^{48}Ca,xn)^{279-x}Rg$

Reactions (n-rich):

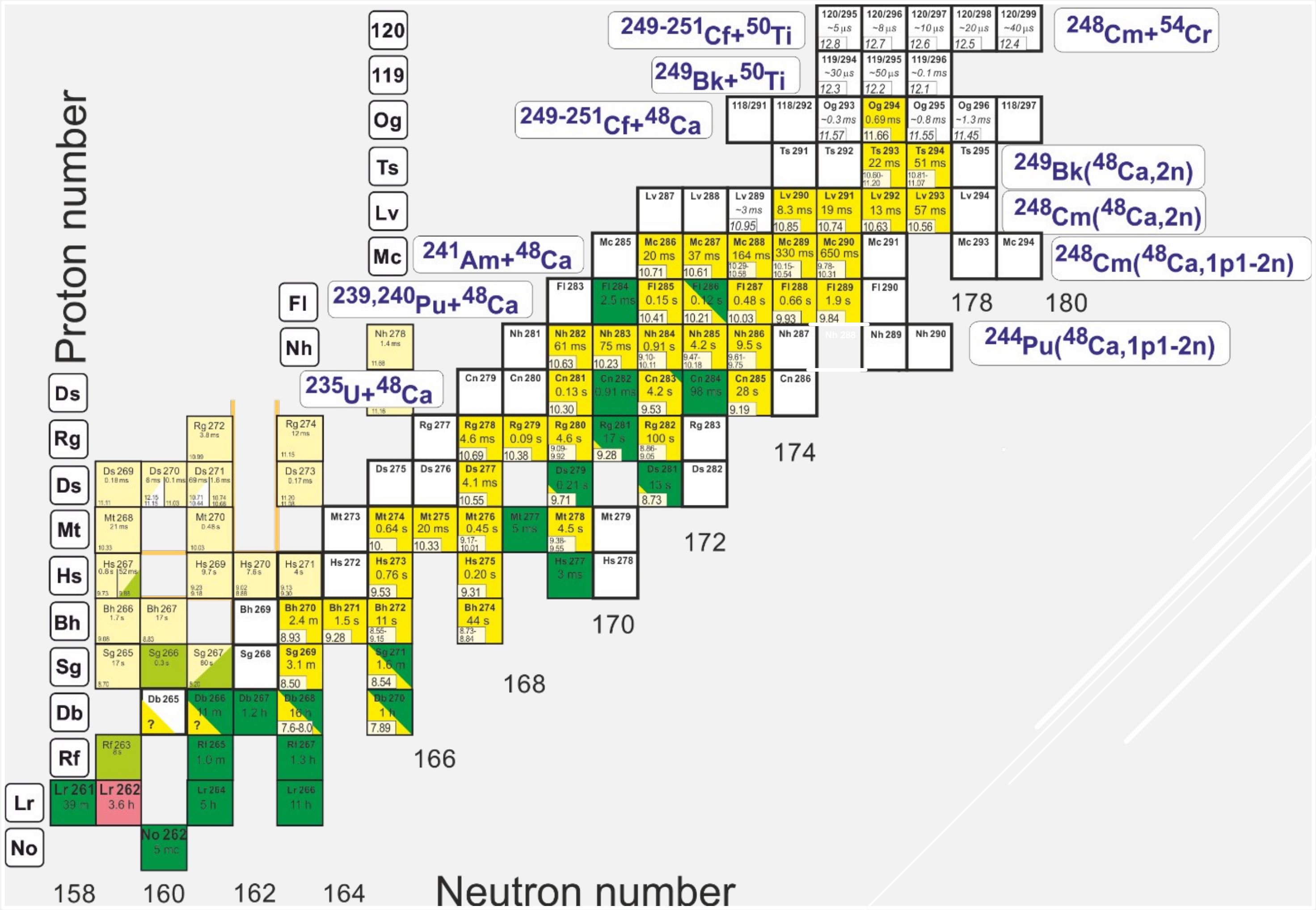
$^{249}Bk(^{48}Ca,2n)^{295}Ts_{178}$

$^{248}Cm(^{48}Ca,2n)^{294}Lv_{178}$

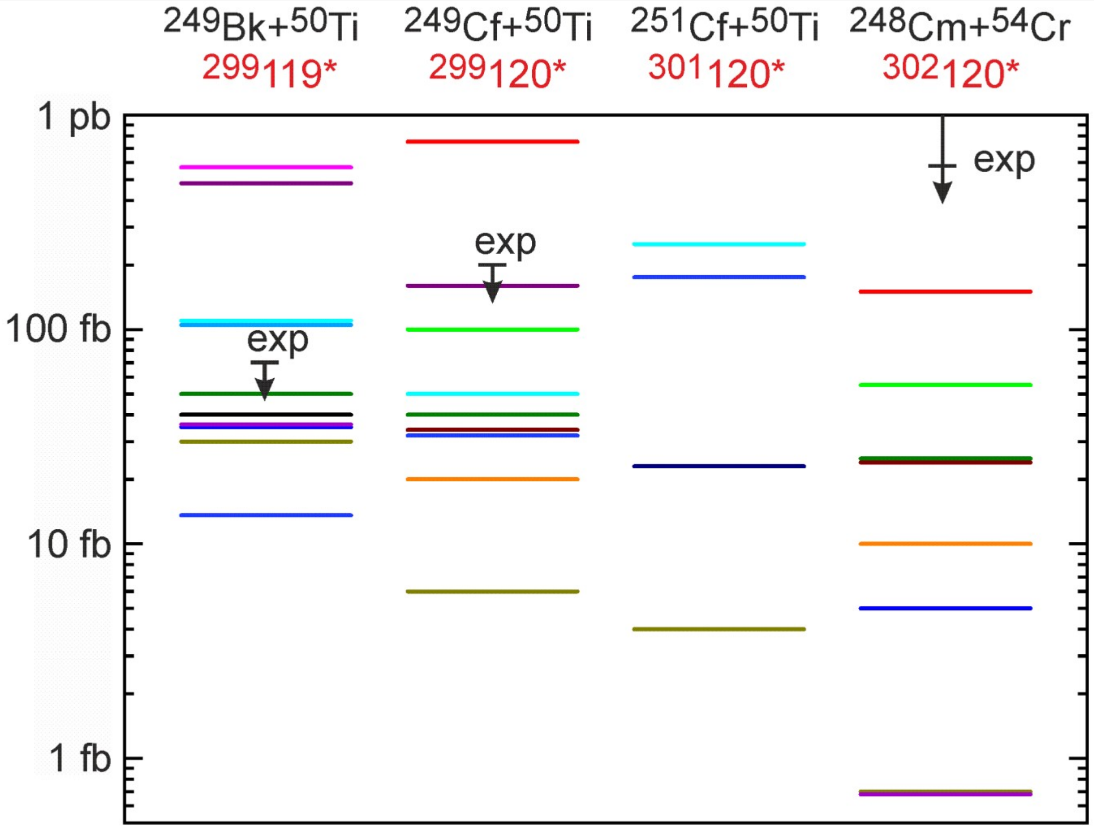
$^{248}Cm(^{48}Ca,1p1\text{-}2n)^{293-294}Mc_{178-179}$

$^{242,244}Pu(^{48}Ca,1p1\text{-}2n)^{287-290}Nh_{176-177}$

electron capture



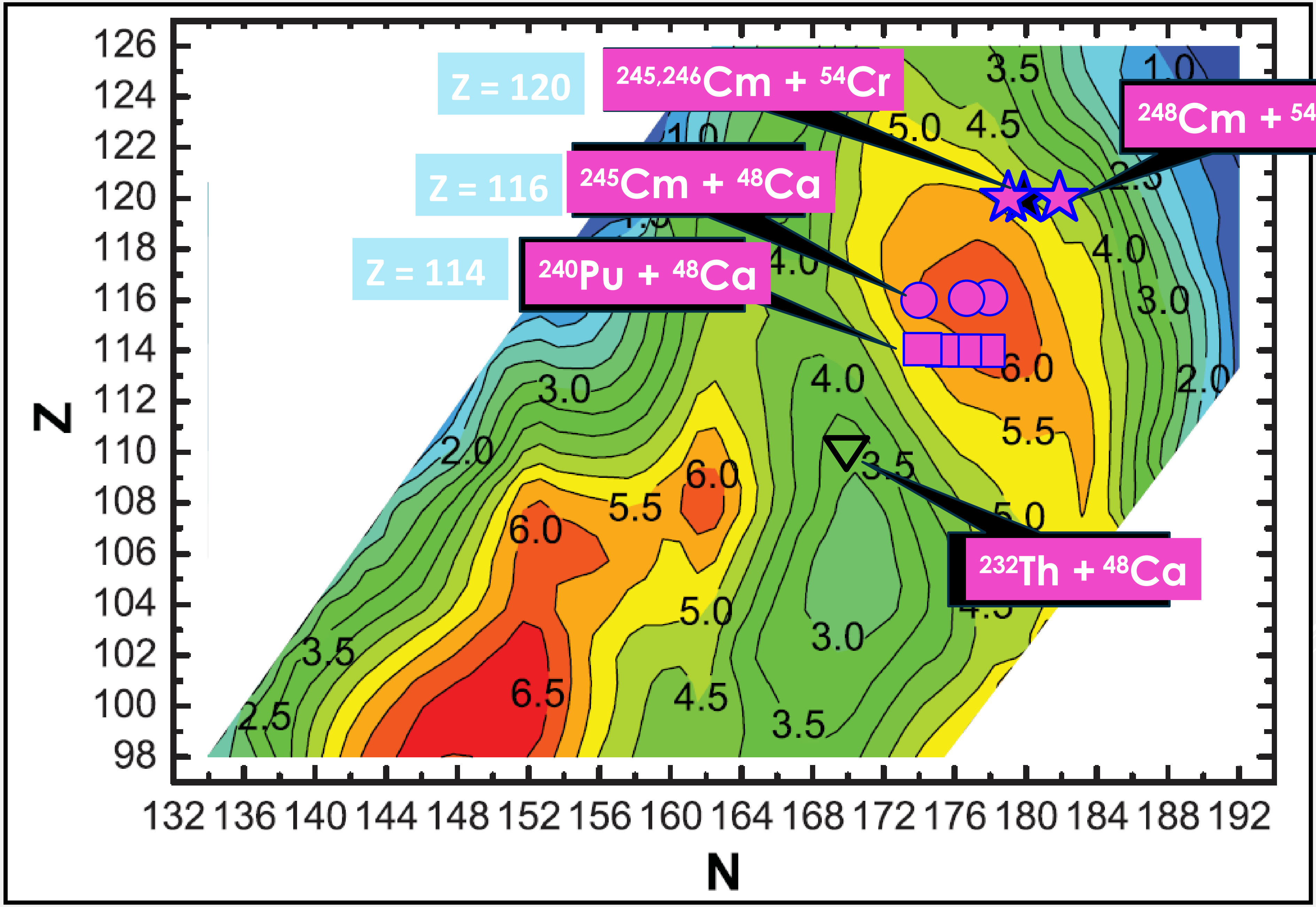
Predicted cross sections for production of isotopes of elements 119 and 120 in the ^{249}Bk+^{50}Ti, $^{249\text{-}251}$Cf+^{50}Ti , ^{248}Cm+^{54}Cr reactions differ by 2-3 orders of magnitude



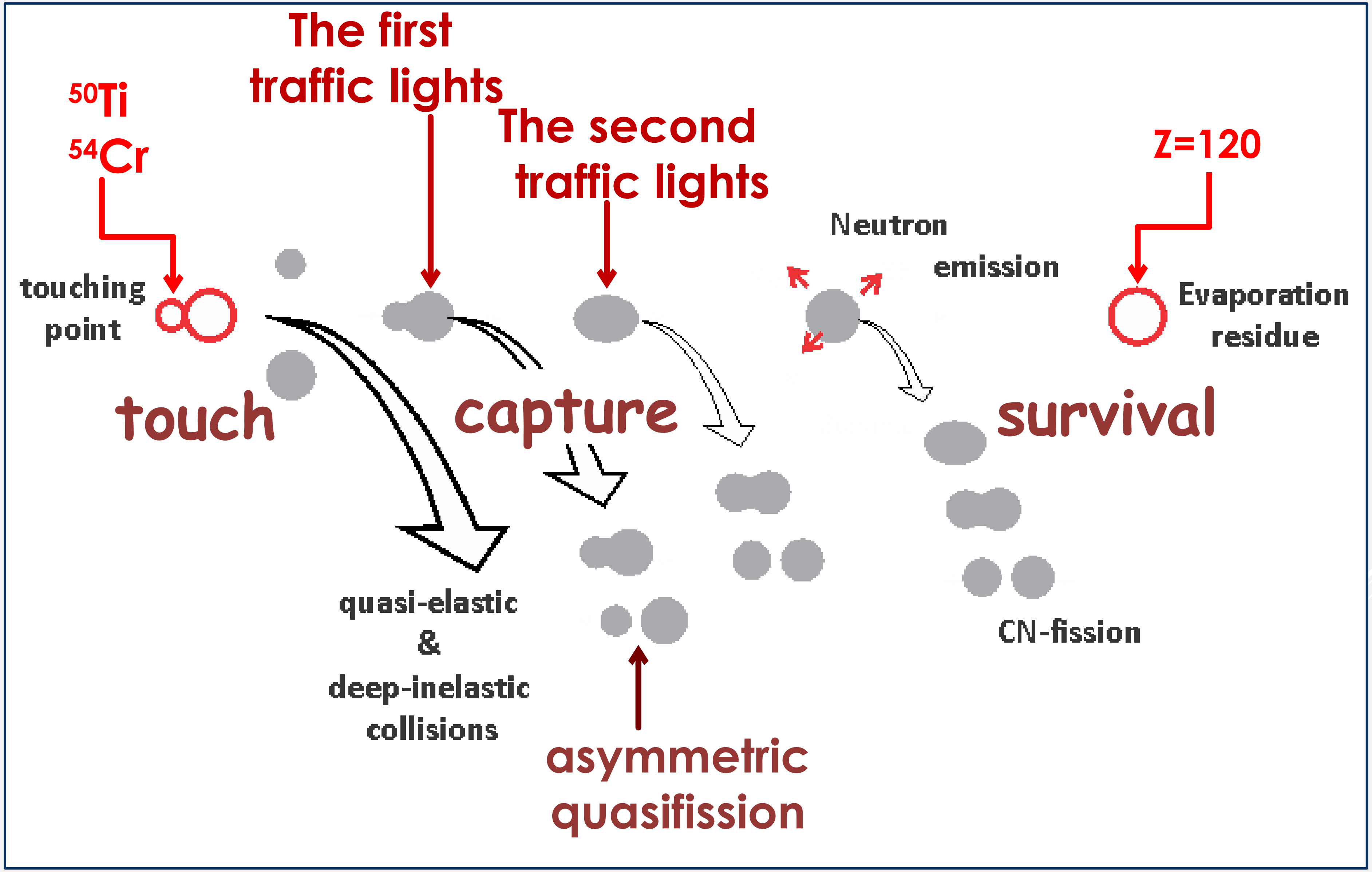
V.I. Zagrebaev *et al.*, Phys. Rev. C **78**, 034610 (2008)
K. Siwek-Wilczynska *et al.*, Int. J. Mod. Phys. E **19**, 500 (2010).
A.K. Nasirov *et al.*, Phys. Rev. C **84**, 044612 (2011).
Ning Wang *et al.*, Phys. Rev. C **84**, 061601 (2011).
Nan Wang *et al.*, Phys. Rev. C **84**, 061601 (2011).
Z.H. Liu *et al.*, Phys. Rev. C **84**, 031602(R) (2011).
K. Siwek-Wilczynska *et al.*, Phys. Rev. C **99**, 054603 (2019).
K.P. Santhosh *et al.*, Phys. Rev. C **96**, 034610 (2017).
K. Siwek-Wilczynska *et al.*, Phys. Rev. C **86**, 014611 (2012).
A.N. Kuzmina *et al.*, Phys. Rev. C **85**, 014319 (2012).
Jinjuan Zhang *et al.*, Nucl. Phys. A **909**, 36 (2013).
Z.H. Liu, J.D. Bao, Phys. Rev. C **87**, 034616 (2013).
V.I. Zagrebaev, W. Greiner, Nucl. Phys. A **944**, 257 (2015).
G. G. Adamian *et al.*, Phys. Part. Nucl. **47**, 387 (2016).
A. Ansari *et al.*, Int. J. Mod. Phys. E **26**, 1750050 (2017).

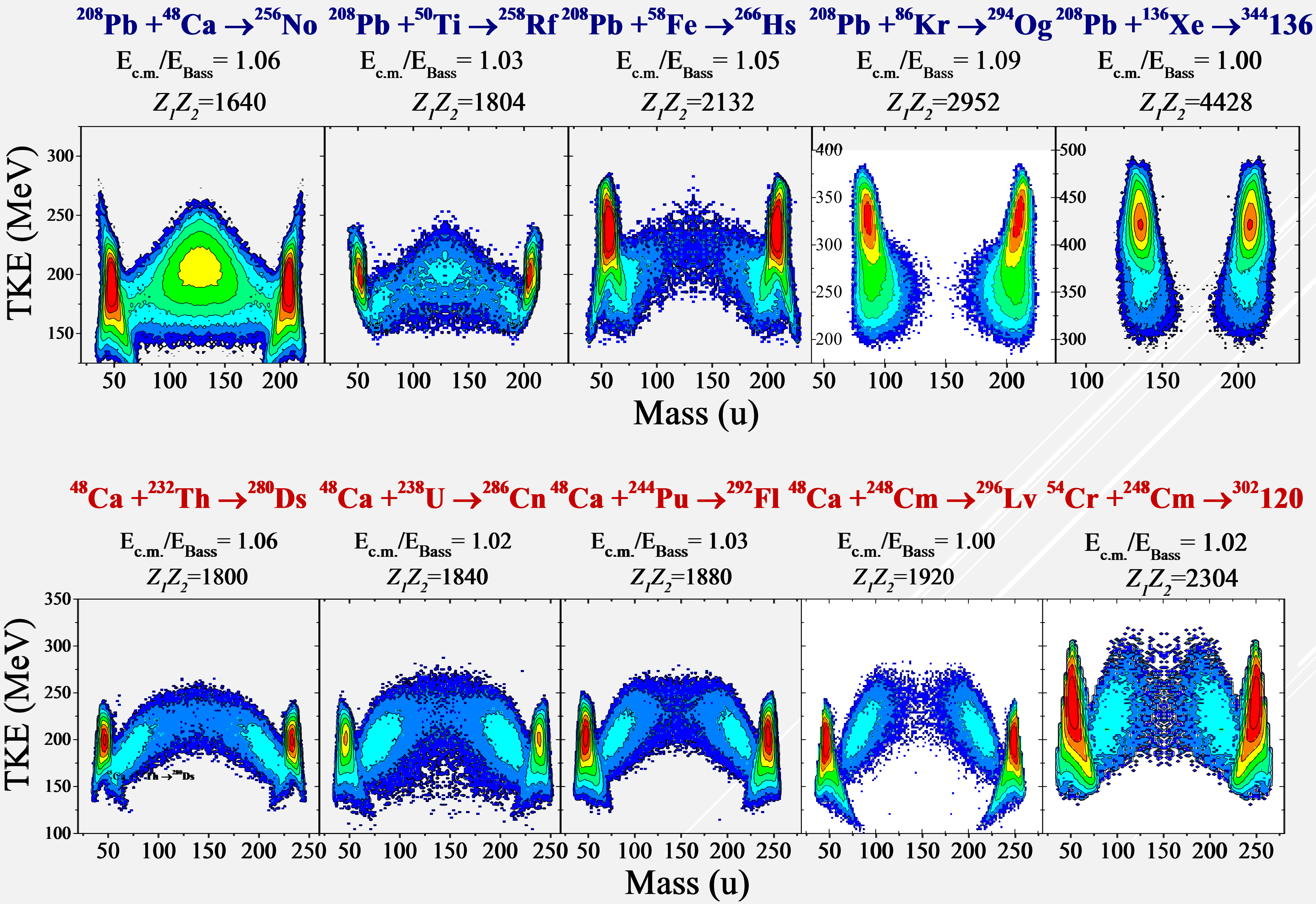
Test reactions are needed

Fission Barriers of Z = 110, 114 и 120



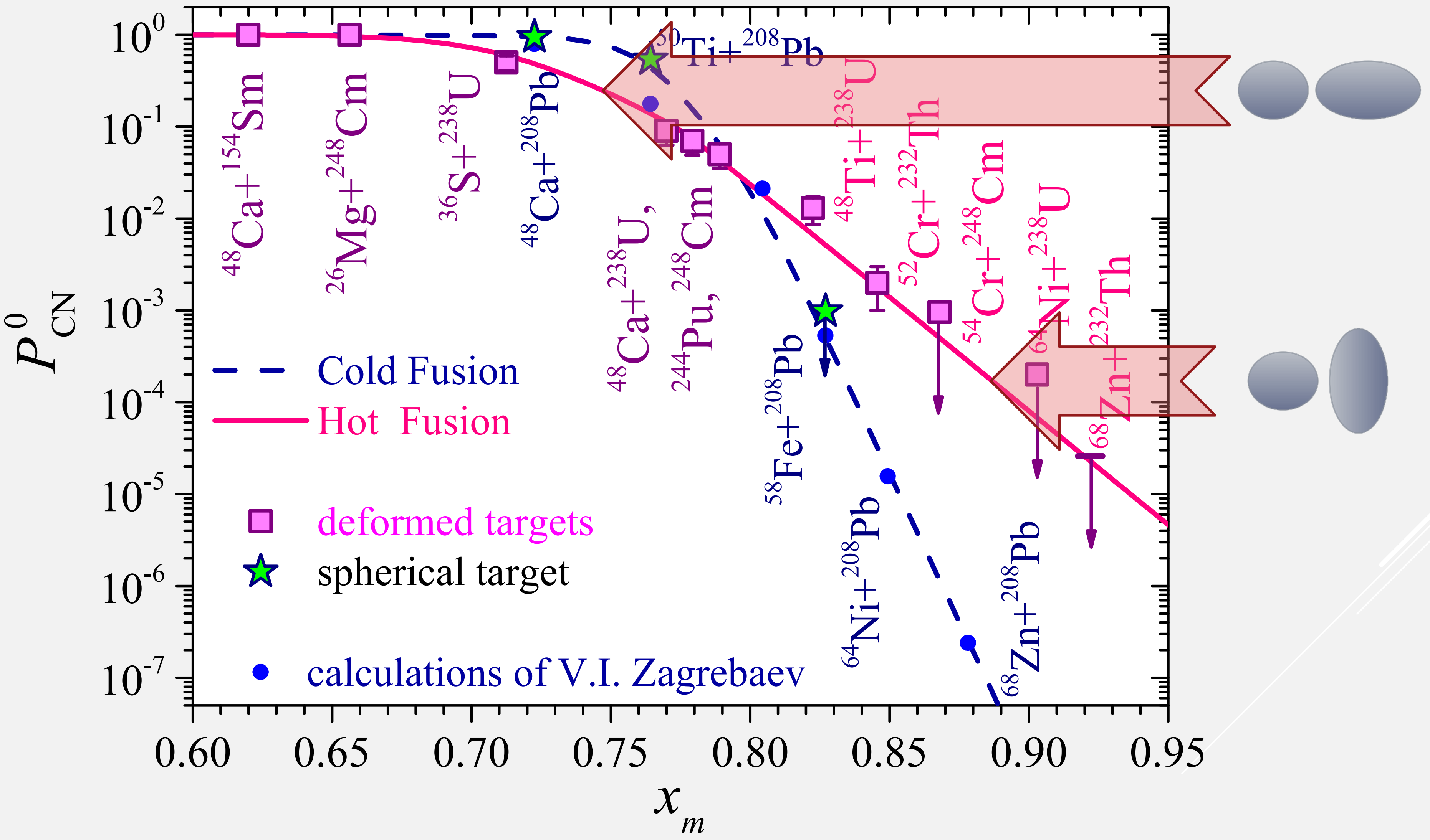
TRAFFIC LIGHTS



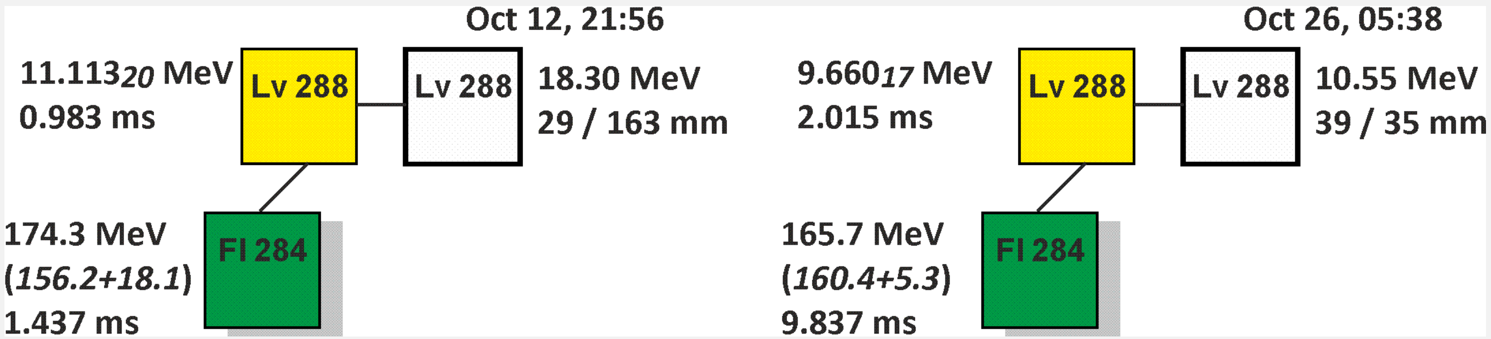


208Pb + 48Ca → 256No
Ec.m./EBass = 1.06
Z1Z2=1640
208Pb + 50Ti → 258Rf
Ec.m./EBass = 1.03
Z1Z2=1804
208Pb + 58Fe → 266Hs
Ec.m./EBass = 1.05
Z1Z2=2132
208Pb + 86Kr → 294Og
Ec.m./EBass = 1.09
Z1Z2=2952
208Pb + 136Xe → 344136
Ec.m./EBass = 1.00
Z1Z2=4428
TKE (MeV)
Mass (u)
48Ca + 232Th → 280Ds
Ec.m./EBass = 1.06
Z1Z2=1800
48Ca + 238U → 286Cn
Ec.m./EBass = 1.02
Z1Z2=1840
48Ca + 244Pu → 292Fl
Ec.m./EBass = 1.03
Z1Z2=1880
48Ca + 248Cm → 296Lv
Ec.m./EBass = 1.00
Z1Z2=1920
54Cr + 248Cm → 302120
Ec.m./EBass = 1.02
Z1Z2=2304
TKE (MeV)
Mass (u)

Fusion Probability in Cold and Hot fusion reactions



Experiment $^{238}U + ^{54}Cr$



<u>For the first time:</u>

Actinide + ^{54}Cr

New isotope ^{288}Lv

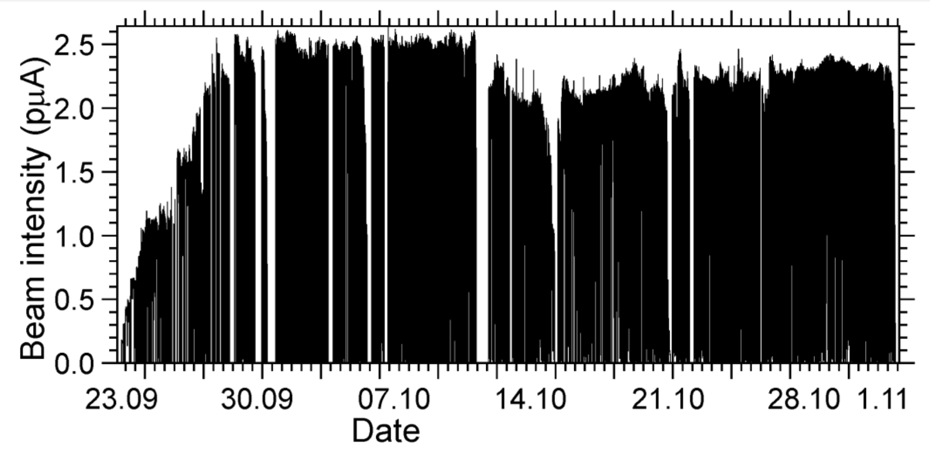
Confirmation of ^{284}Fl

Target ^{238}U: 0.72 mg/cm^2

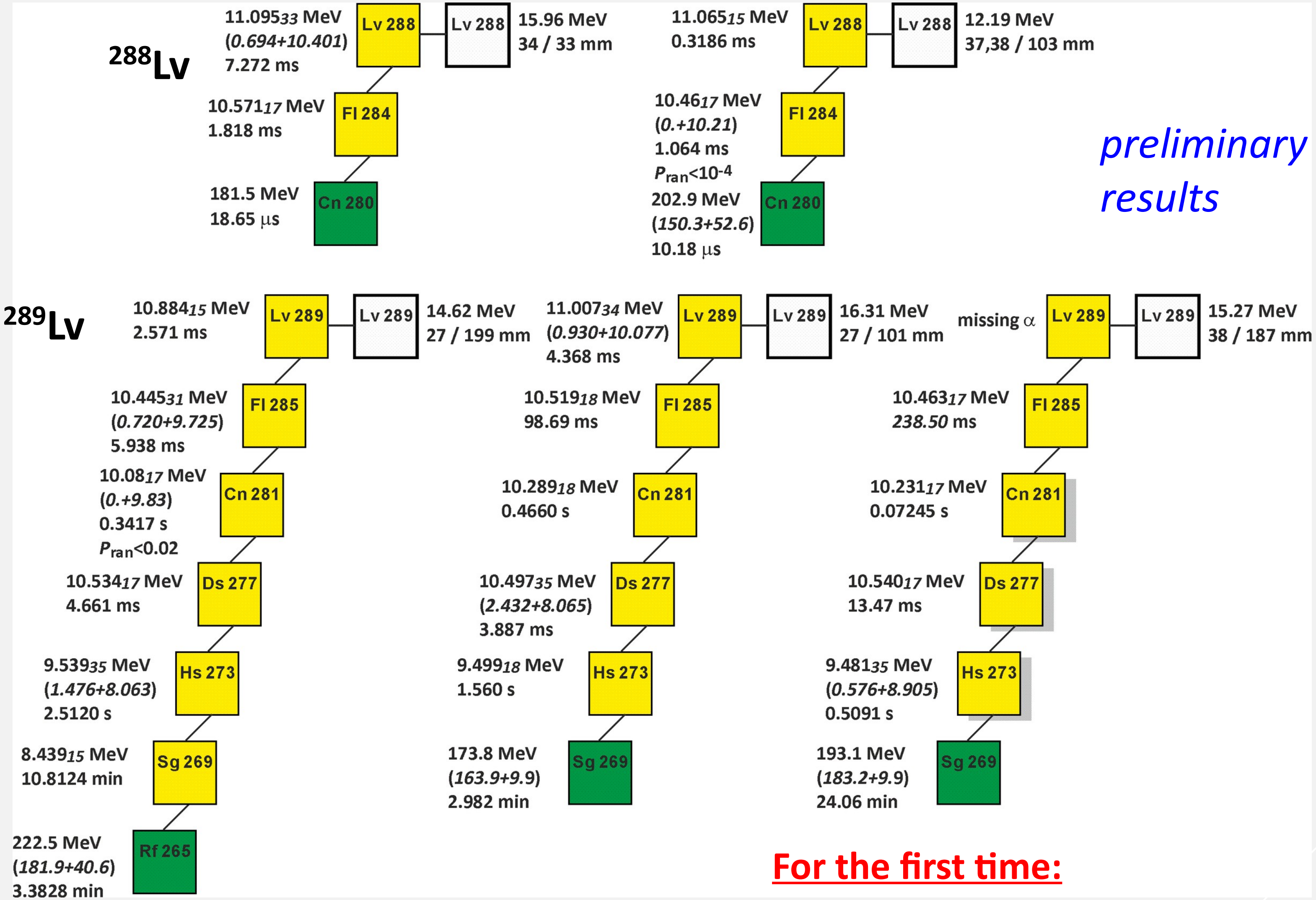
Beam dose: 2.6 x 10^{19}

Excitation energy: 42 MeV

Cross section 0.1 pb



Experiment $^{242}Pu + ^{50}Ti$



Target ^{242}Pu: 0.73 mg/cm^2

Beam dose: 1.5 x 10^{18}

Excitation energy: 41 MeV

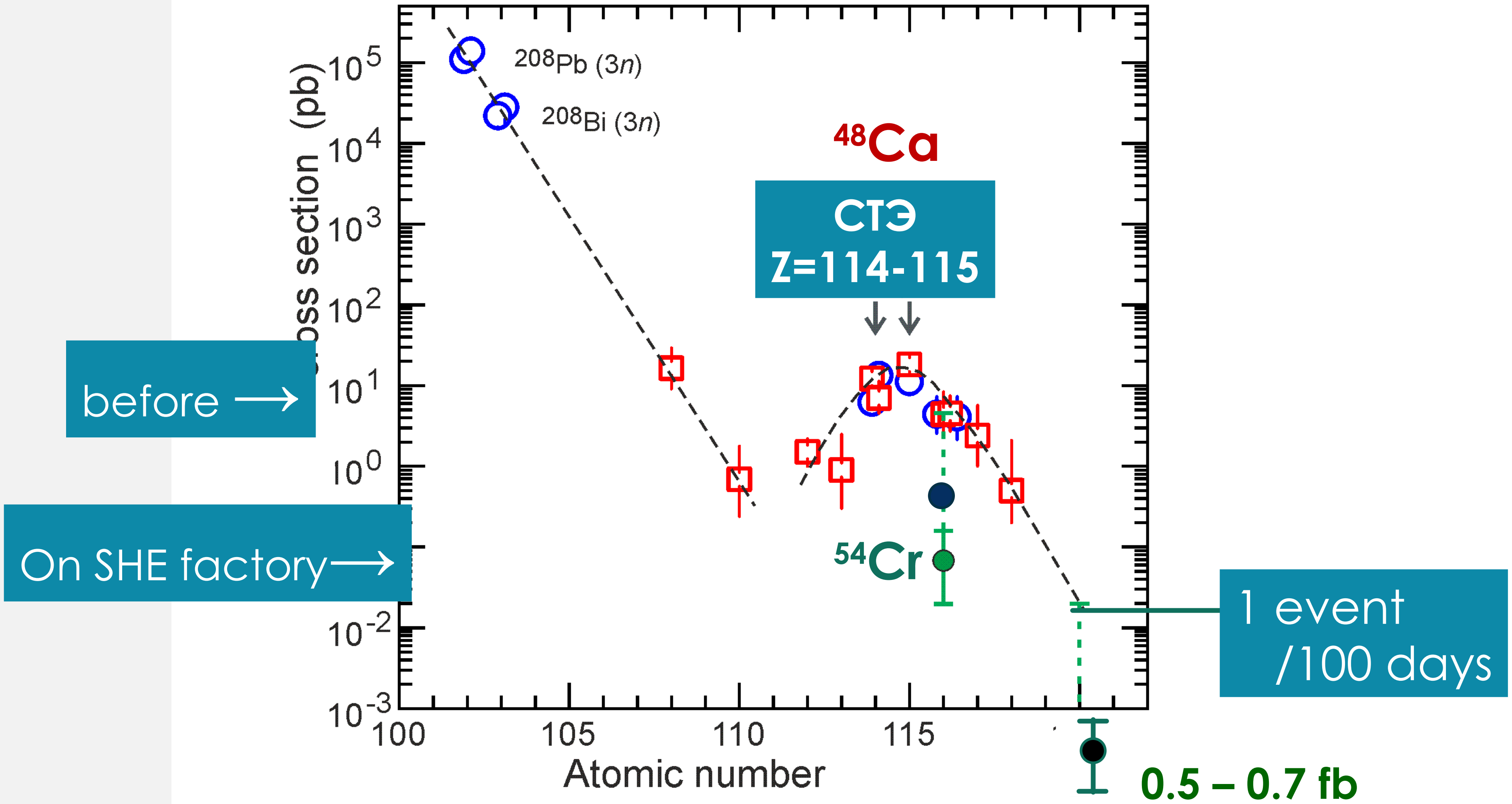
For the first time:

New isitope ^{289}Lv

α-decay of ^{289}Lv

Cross section: ~0.54 pb

Synthesis of 120 and consequence

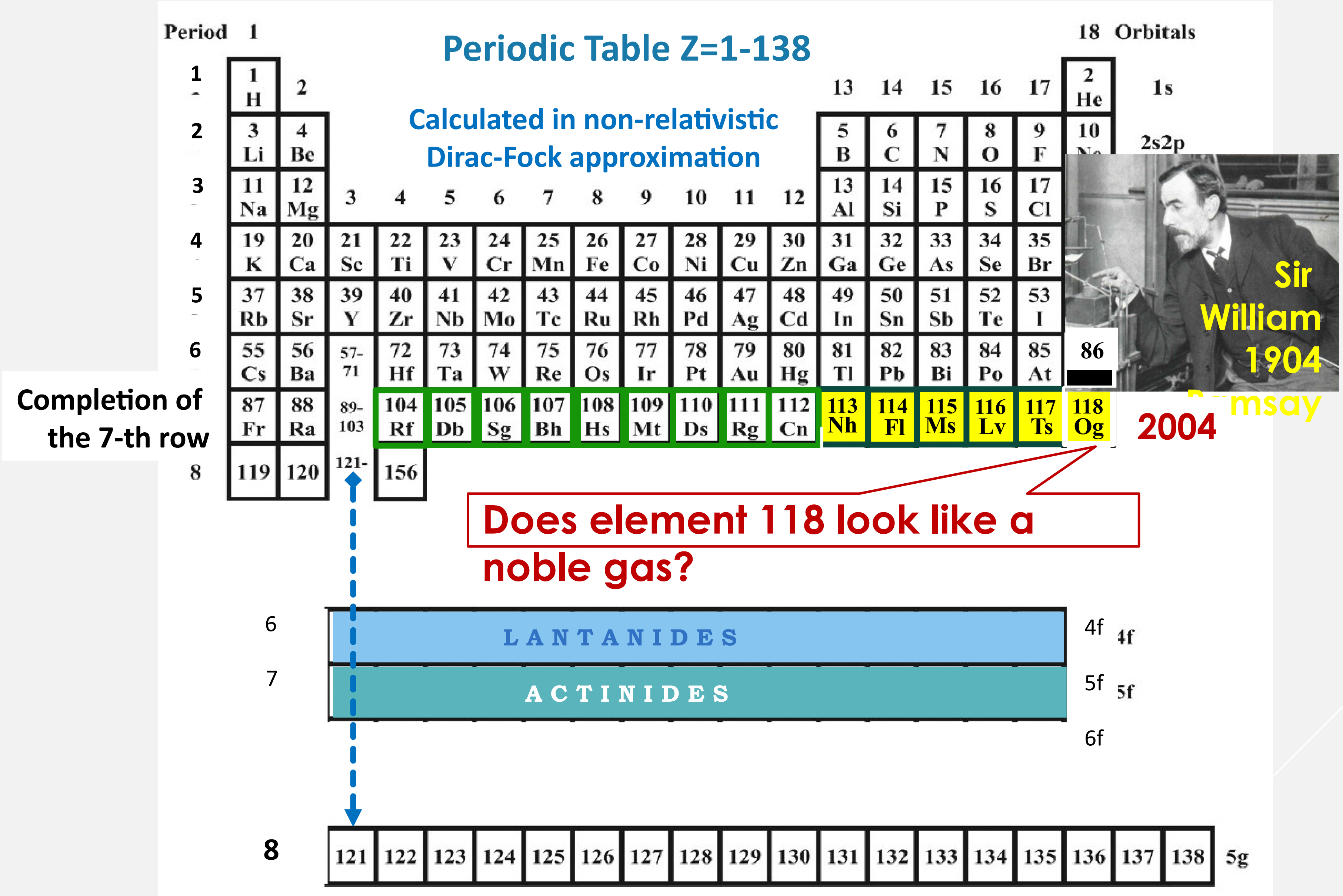


REACTION MECHANISMS IN DEPENDENCE ON Z_1Z_2

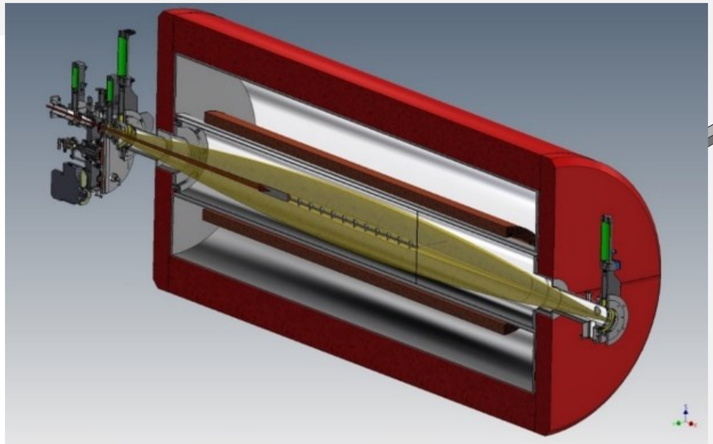
Z_1Z_2	Reactions with actinide targets	Reaction mechanisms
1472	$^{36}S + {}^{238}U$ (Z_{CN} = 108)	At energies below the Coulomb barrier the dominant reaction channel is asymmetric quasifission. At energies above the barrier, the upper limits for CN-fission is ~30%.
1840 ÷ 1920	$^{48}Ca + {}^{238}U, {}^{244}Pu, {}^{248}Cm$ (Z_{CN} = 112, 114, 116)	The dominant process is asymmetric quasifission. At energies above the barrier, the upper limits for CN-fission is ~5-10%.
2024 ÷ 2304	$^{48}Ti + {}^{238}U$, $^{52}Cr + {}^{232}Th$, $^{52,54}Cr + {}^{248}Cm$ (Z_{CN} = 114, 114, 120)	The dominant process is asymmetric quasifission. At energies above the barrier – the upper limits for CN-fission is ~0.1-1%.
2576 ÷ 2700	$^{64}Ni + {}^{238}U, {}^{68}Zn + {}^{232}Th$ (Z_{CN} = 120)	The dominant processes are deep-inelastic collisions and a few nucleon transfer. The formation of symmetric fragment even in QF is strongly suppressed.

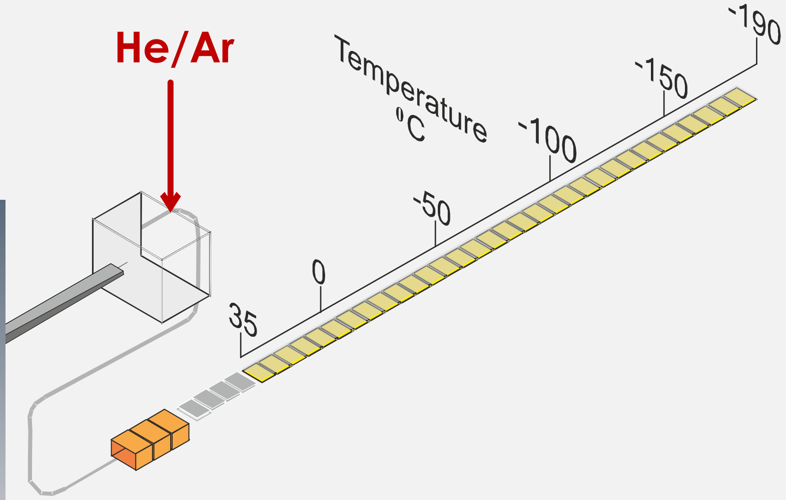
Будет ли элемент 118 бдагородным газом?

Giant (284 m²) Periodic Table Dubna, 2021


Periodic Table Z=1-138
Calculated in non-relativistic
Dirac-Fock approximation
Period
Orbitals
1s
2s2p
Completion of the 7-th row
Sir William 1904
msay
2004
Does element 118 look like a noble gas?
LANTANIDES
ACTINIDES
4f
5f
6f
5g
113 Nh
114 Fl
115 Ms
116 Lv
117 Ts
118 Og
119
120
121-
156
121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138

CHEMISTRY OF SHE

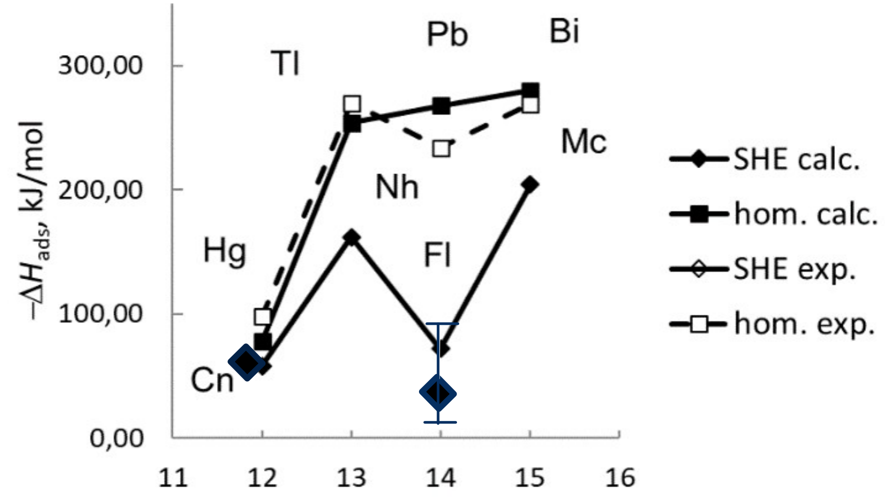




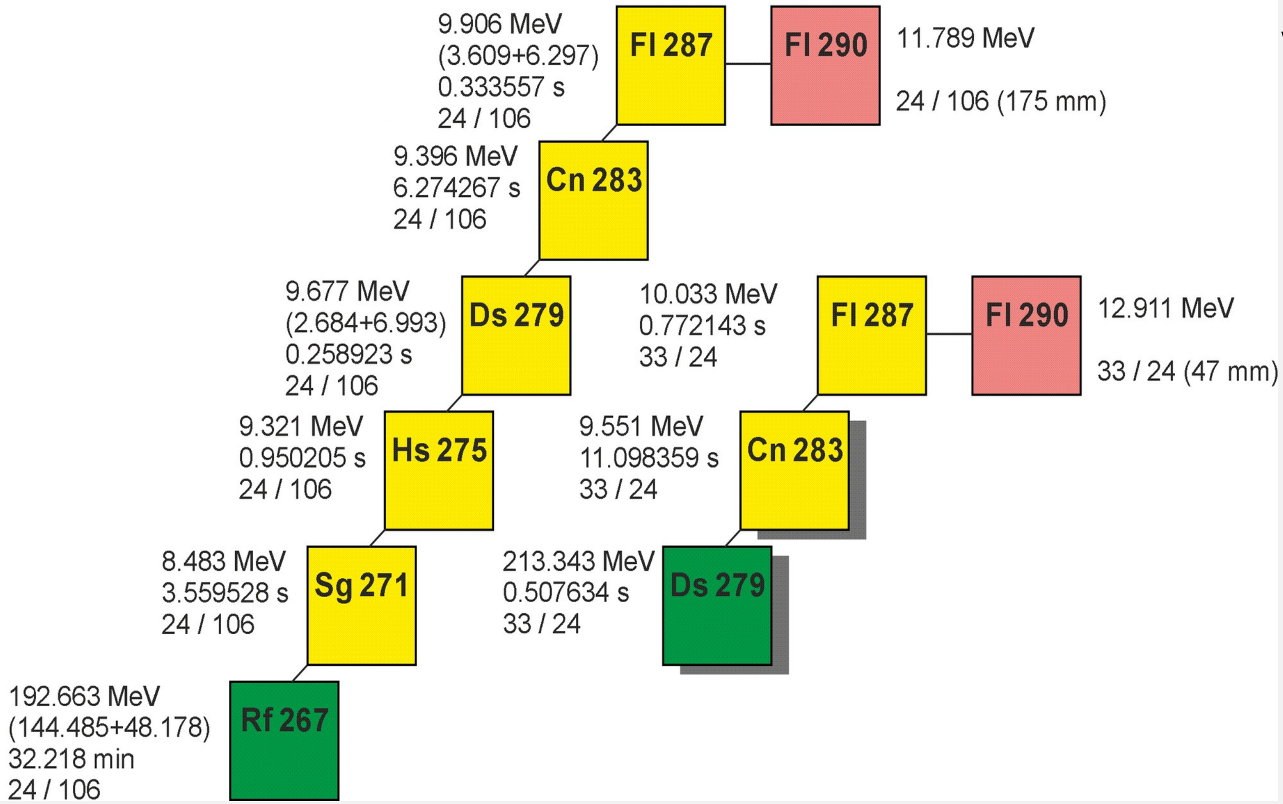
Z	Isotope	Half-life
112	^{283}Cn	3.6 s
113	^{284}Nh	0.9 s
114	^{287}Fl	0.3 s
115	^{288}Mc	0,16 s
116	^{293}Lv	57 ms
117	^{294}Ts	51 ms
118	^{294}Og	0.6 ms

GASSOL – Solenoid-based separator

- *Stopping SH atoms in a small volume of 1-2 cm³*
- *Chemistry of short-lived SHE $T_{1/2} \geq 30$ ms (up to elements 116-117)*

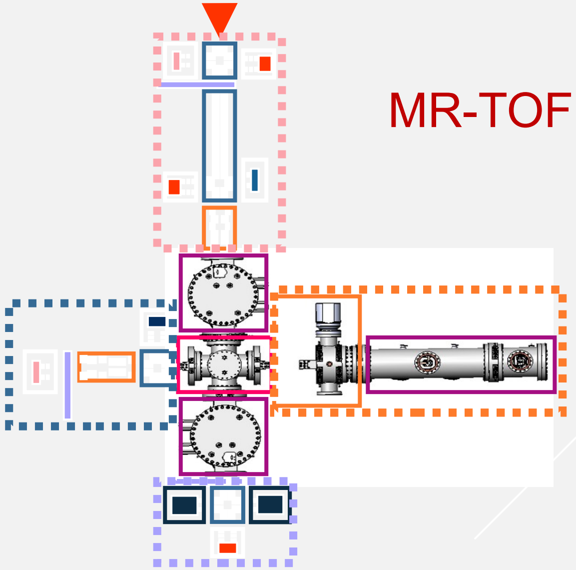


Precise mass measurements of SH nuclei @ SHE Factory



Measuring masses of SH isotopes with accuracy 10^{-7} (30 кeV)

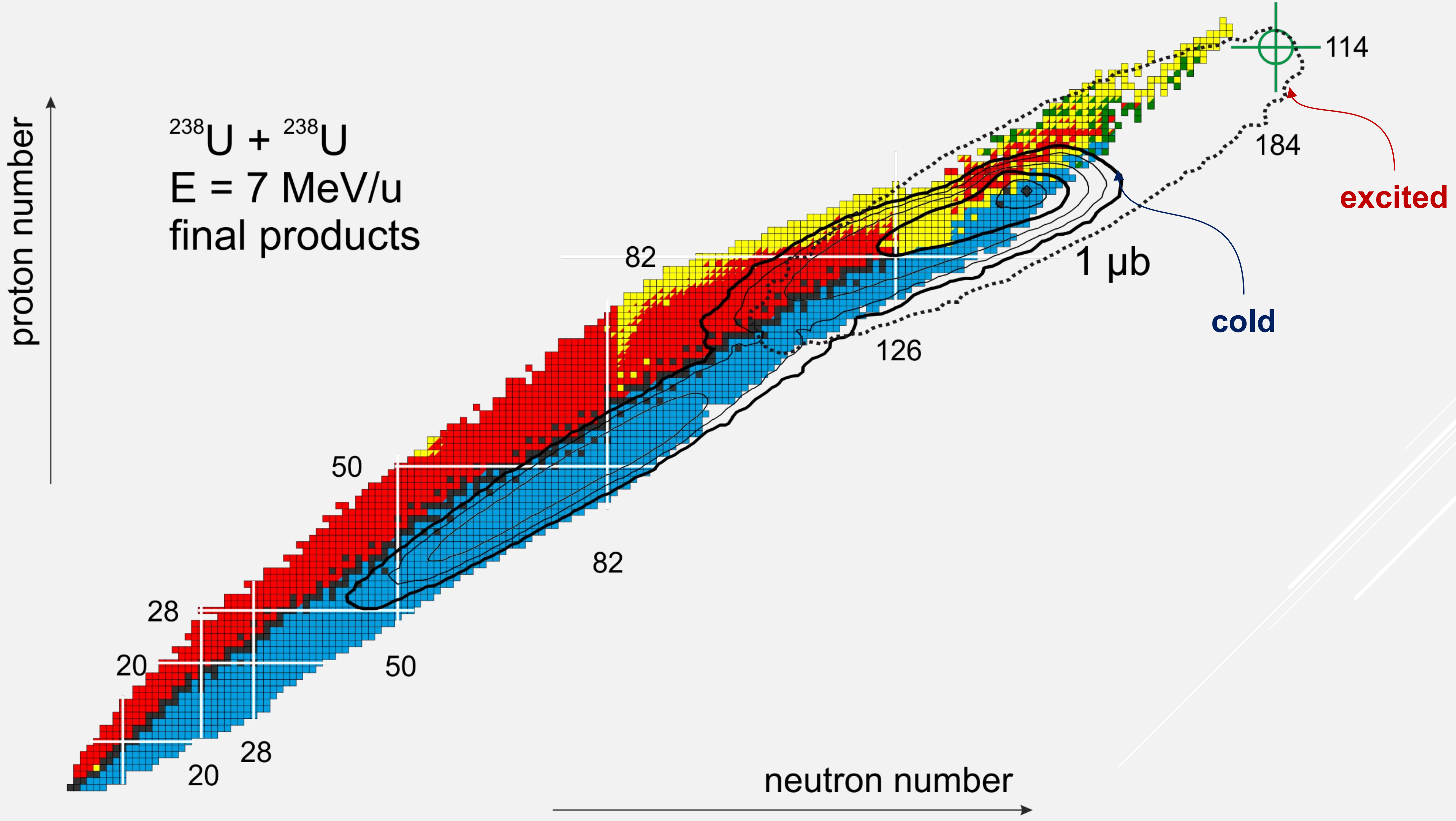
- $T_{1/2}$ < 0.5 s
- Production rate 1 event/day
- Background rate event/s



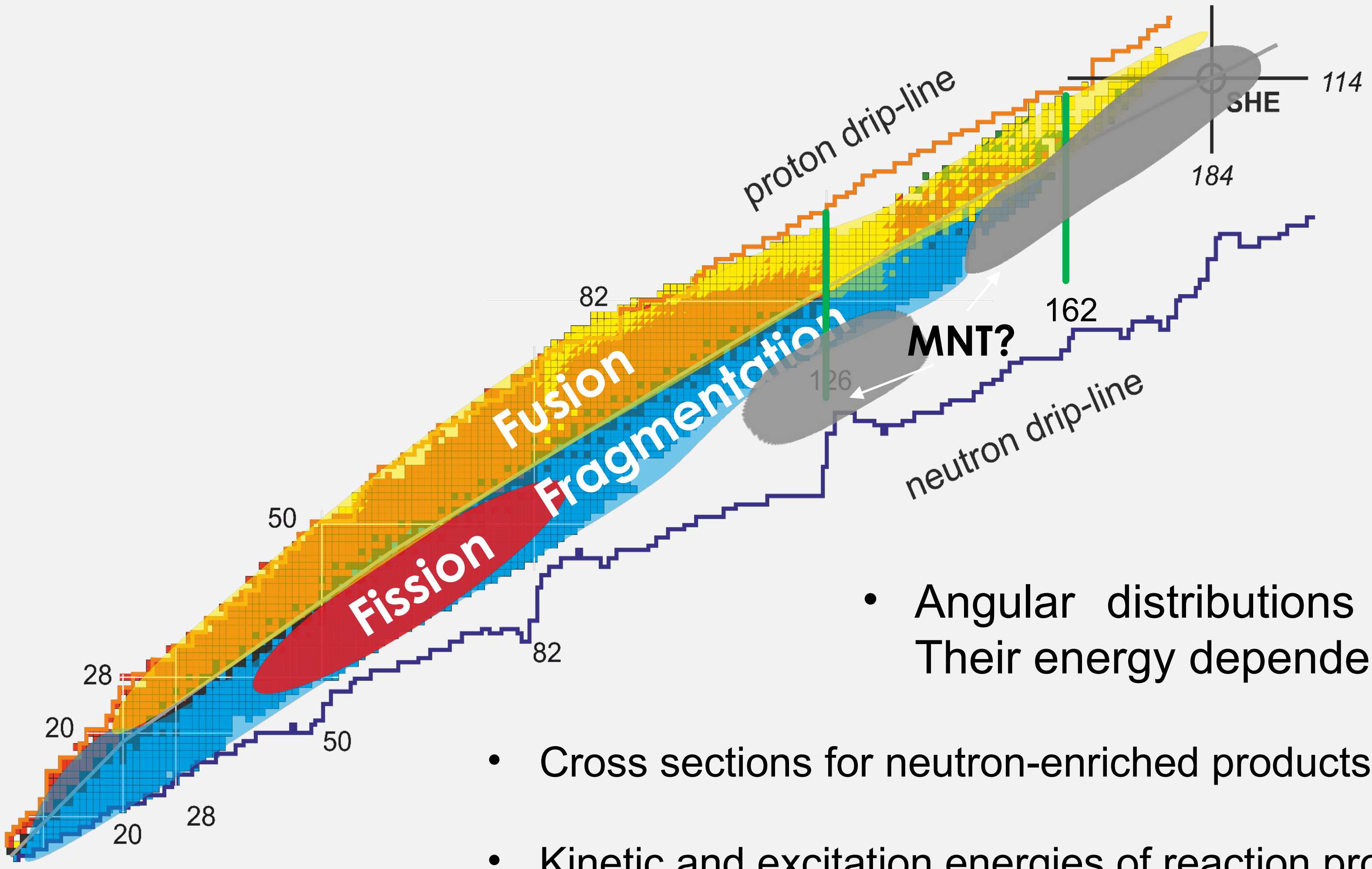
MR-TOF Mass-Analyzer

M.I. Yavor, Journal of Instrumentation, ***17*** *(2022) 11033*

Multinucleon transfer processes in U + U reaction



Multinucleon transfer reactions. Some of the open questions



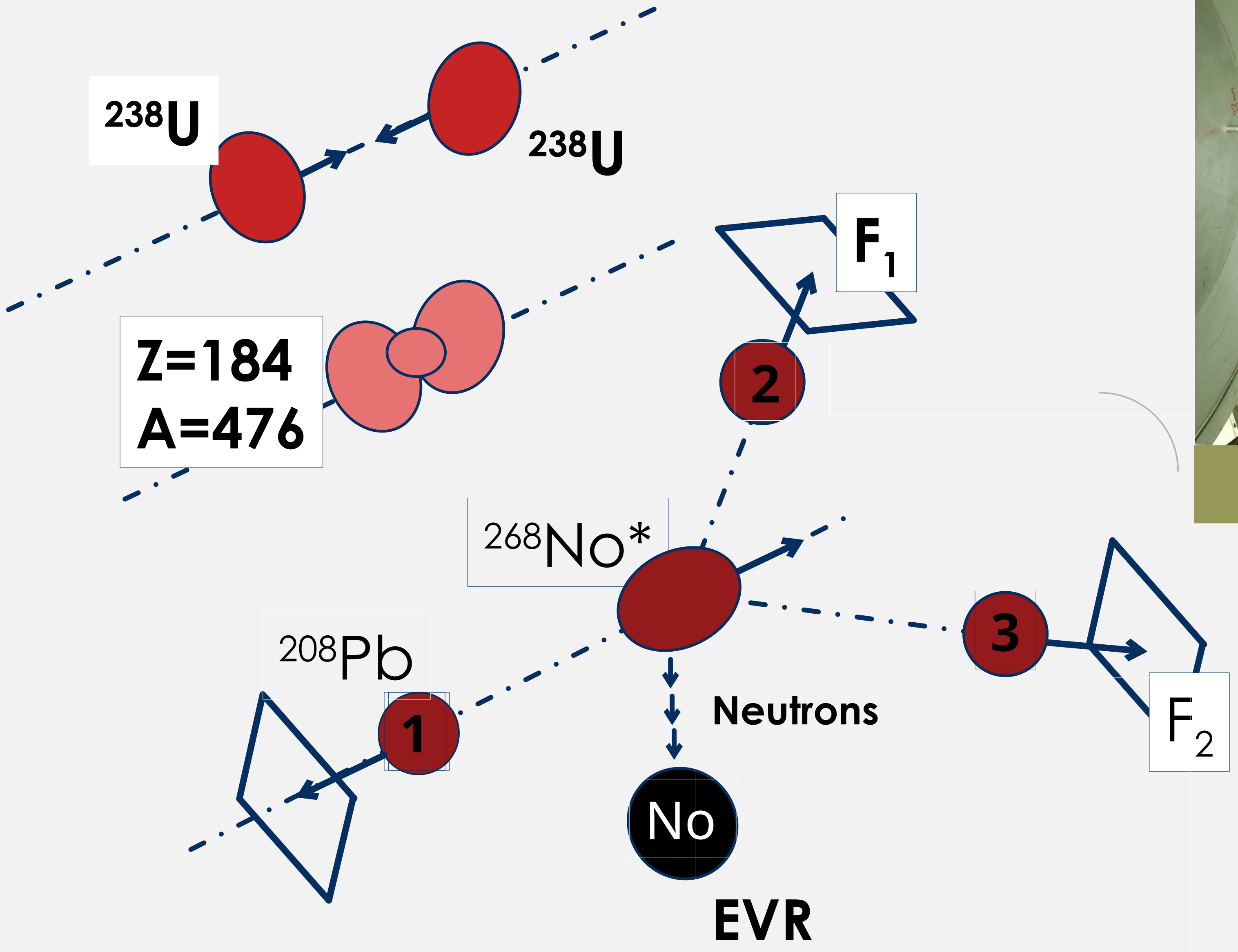
- Angular distributions of various reaction products. Their energy dependence.

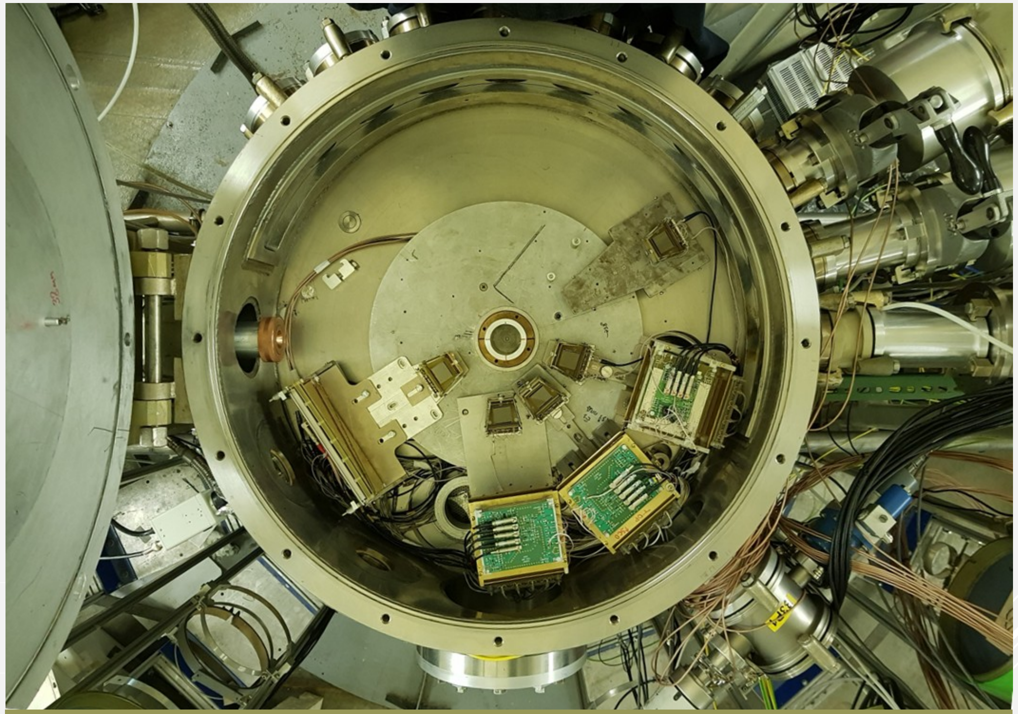
- Cross sections for neutron-enriched products. Their energy dependence.

- Kinetic and excitation energies of reaction products.

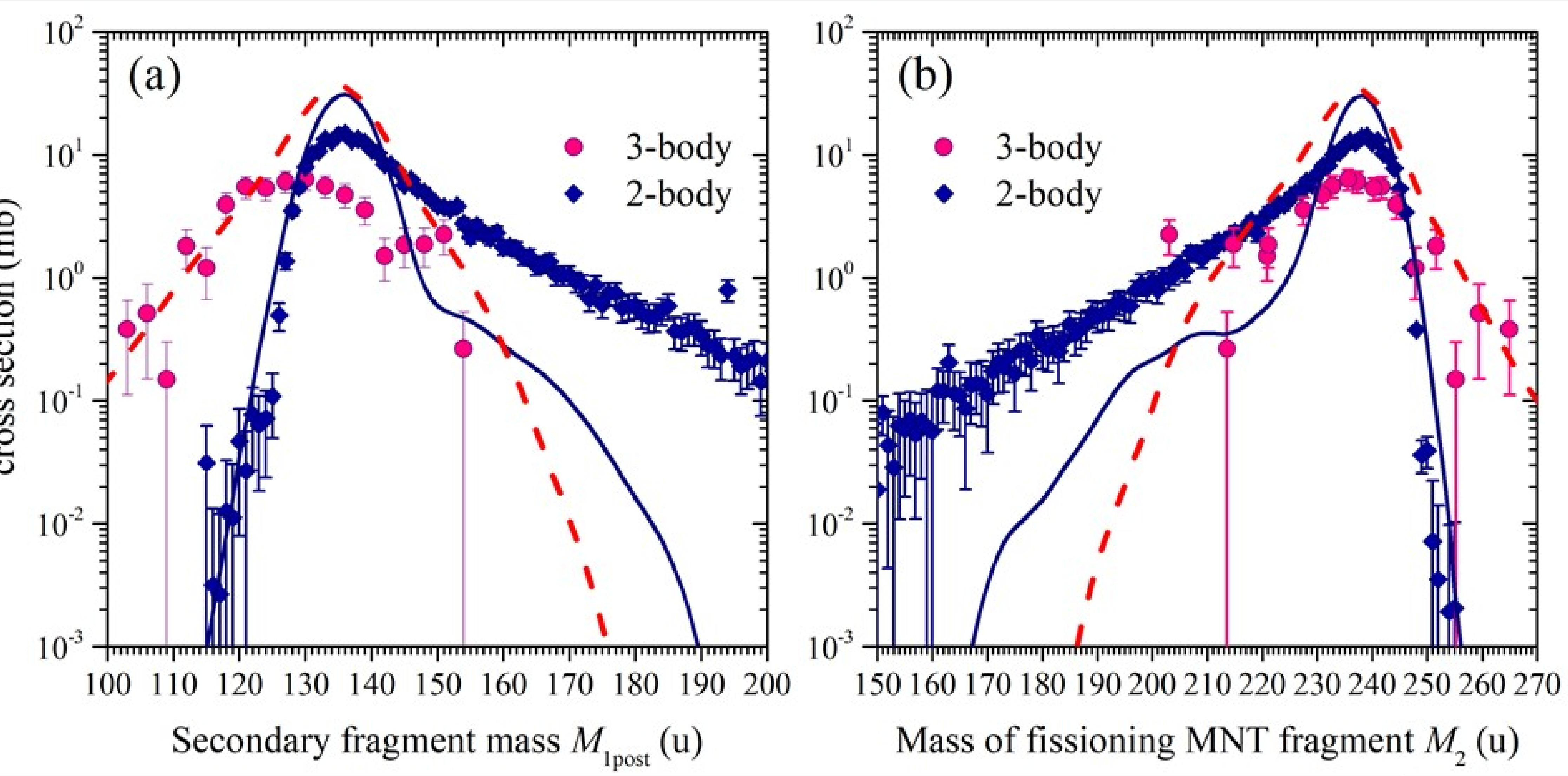
- Optimal reaction choice for production of various nuclei in heavy (*N*=126) and transuranium mass regions.

Studying the $^{238}U + ^{238}U$ reaction

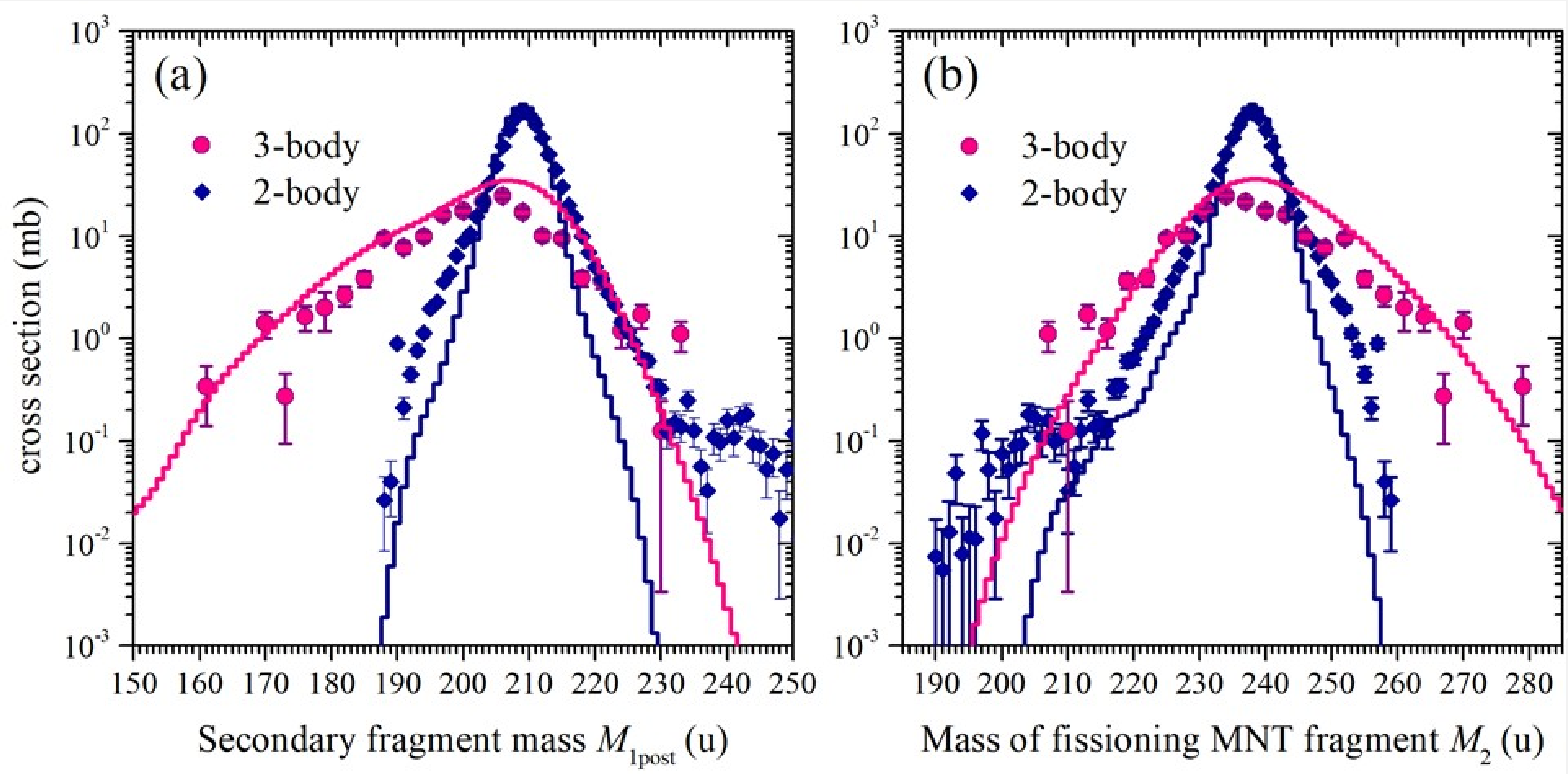




Modernized COREST set-up



cross section (mb)
(a)
3-body
2-body
Secondary fragment mass M_{1post} (u)
(b)
3-body
2-body
Mass of fissioning MNT fragment M_2 (u)


(a)
3-body
2-body
cross section (mb)
Secondary fragment mass M_{1post} (u)
(b)
3-body
2-body
Mass of fissioning MNT fragment M_2 (u)

Thank You!